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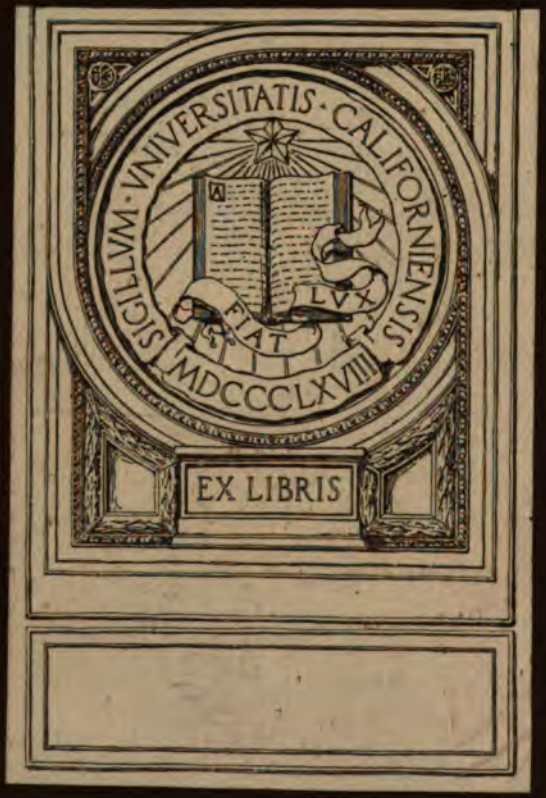
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# ELECTRIC FURNACES

IN THE

# IRON AND STEEL INDUSTRY

BY

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# PREFACE TO THE GERMAN EDITION

ELECTRIC furnaces and their use in the manufacture of steel and iron have been described in books by Borchers, Neumann Askenasy, and others. Their treatises have either described so fully the whole subject of electro-metallurgy that only a very small space could be allotted to electric iron and steel, or else, as in Neumann's volume, only a glance is given at the early experiments which were made when these furnaces were first introduced.

Hence, there is need for a work thoroughly describing electric furnaces, which are designed only for the steel and iron industry.

For practical reasons the book is divided into two parts, of which the first deals with all questions relative to the construction of these electric furnaces, and the apparatus used, while the other part takes up the practical use of electric furnaces in the steel mill and all its metallurgical reactions.

While undertaking this work the authors were conscious of the difficulty of describing each type of furnace entirely from personal observation. This difficulty, however, confronts all who are similarly situated, as these electric furnaces have only recently been introduced into the iron trades and it is practically impossible to know each type from one's own experience.

As both practical and theoretical men differ regarding the advantages of these furnaces for steel and iron making, it is not to be expected from this book that any one type of furnace is pictured as being better than any other type. Wherever possible, therefore, results are given which are based on actual experience, although much other material has been used.

THE AUTHORS.

VÖLKLINGEN, SAAR, 1911.



267479

# PREFACE TO THE EDITION IN ENGLISH

THE preparation of this work in English was undertaken in the belief that electric furnaces for the iron and steel industry would have their greatest future on the North American Continent. Especially is this true of furnaces making electric steel. Specifications are daily becoming stricter for steel rails, steel castings, and tool steel. Electric steel rails, costing but little more than the ordinary kind, are found to be unbreakable in service, when laid beside open hearth and Bessemer rails. In these latter, scores of breakages have occurred in one season. The future of electric steel rails consequently seems assured.

Electric steel castings have also been on the market for the past four years. They are looked upon with favor alike by the foundryman and the customer, not only because the highest class of steel may be made from the cheapest raw material, but also because of the high percentage of good castings and their freedom from blow-holes.

The ability to make homogeneous tool steel, free from gases, and at low cost, brought the electric furnace into commercial use over a decade ago. In this field it promises to displace completely the old and small crucible pot which has been in use since the year 1740.

With these three principal fields now open to electric furnace products, it cannot be long before all other domains in the use of steel will be invaded. The cost of producing electric steel is lower now than that of the crucible process, or of the small converter process, and even less than that of the open hearth process, as practised with 10-ton furnaces or under. A success can, therefore, be confidently predicted for electric furnaces and their manufacture of iron and steel.

A few changes were found necessary, in adapting the German to the edition in English, and some fresh material has been added.

The translator gladly takes this opportunity to thank many friends for information and assistance. Dr. G. B. Waterhouse, of Buffalo, kindly gave the benefit of his extended experience in connection with the metallurgy of iron and steel as set forth in Part II of this book. To Mr. A. H. Strong, of New York, special thanks are due for valuable aid rendered in the various chapters on induction furnaces. Mr. Magnus Ugner, of the transformer and furnace department of the General Electric Company, very kindly read the proofs of many chapters of Part I. No one has had a larger or more successful experience in building transformers and furnaces than Mr. Unger. Finally, thanks are due to Dr. D. A. Lyon for much new material added, mainly to the chapters on electric pig-iron furnaces.

C. H. VOM BAUR.

NEW YORK, *September 7th*, 1912.

# PREFACE TO PART I

THE realm of Steel and Iron manufacture has in the past ten years had a new world of possibilities opened to it by the introduction of the electric furnace. Before finding a commercial foothold among ironmasters, it was in use making ferro alloys. Even earlier than this the electric furnace was manufacturing aluminum and calcium carbide.

It has been the aim of the present publication on Electric Steel and Iron Furnaces to produce a book for the practical man; a comprehensive manual of practical information, yet one explaining the electric laws and phenomena involved, and the scientific principles upon which the work rests. The understanding of these electrical laws is practically necessary, for in electric furnace literature we constantly find assertions contradicting the simplest of them. The authors also hope in this manner to render the book of service to the general student of this branch of Electro-Chemical Engineering, and to state especially the principal laws which the construction and operation of electric furnaces entail, without giving long mathematical discussions. Short arithmetical examples nevertheless are given dealing with actual furnace problems. Care has been taken to mention only those things which have some value in the development of Electric Steel and Iron furnaces, rather than to dwell upon theories of little moment. The furnaces most extensively used, such as those of Stassano, Héroult, Girod, Kjellin, and Röchling-Rodenhauser are described in detail, and compared with an ideal Electric Furnace. This seems to be the best course to pursue, for in this way an unfair criticism of the different systems can best be avoided.

In Chapter XIV, "General Review," some furnace designs are briefly discussed which have obtained only a limited use or

which have not yet left the experimental stage, and finally, the electric shaft furnace is described at length.

The discussions are accompanied by a large number of cuts and reproductions.

The demands of actual practise have always been given the greatest consideration. Accordingly, the latest results obtained from good trials with electrodes in arc furnaces are mentioned, as are others of the same order. This volume should, therefore, be a welcome adviser to the furnace builder, the student, and in fact to anybody who is interested in electric furnaces for the production of steel and iron.

The authors have written in the hope that these pages will aid in the further expansion and success of the electric iron and steel trade.

WM. RODENHAUSER.

VÖLKLINGEN, SAAR, 1911.

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# INDEX TO ABBREVIATIONS USED IN PART ONE

A = Work or Energy.

Cos $\phi$ = Power factor.

E = Potential per phase.

e = Potential in volts = Effective value for A. C.

$\bar{e}$ = Maximum value of potential.

e′ = Instantaneous value of potential.

$e_L$ = Potential to overcome the self-induction.

$e_r$ = Potential to overcome the ohmic resistance.

I = Current per phase.

i = Current in amperes = Effective value for A. C.

$i_r$ = Watt component of current.

$i_m$ = wattless component of current.

k = Heat conductivity.

KVA = Kilovolt-amperes.

KW = Kilowatt.

KW Hr = Kilowatt hours.

L = Self-induction.

l = Length of a conductor in metres.

m = Angular velocity.

N = Flux.

p = Power.

p′ = Instantaneous value of power.

Q = Energy in heat units.

q = Section in square millimetres.

r = Resistance in ohms.

s = Turns.

T = Time of a cycle.

t = Time.

VA = Volt amperes.

$\Delta = \frac{i}{q}$ = Current density per square millimetre.

$\nu$ = Cycles per second.

$\rho$ = Specific resistance per 1 metre length and 1 square millimetre section.

$\frac{1}{\rho}$ = Specific conductivity.

$\rho_1$ = Specific resistance per cubic centimetre.

$\rho_2$ = Specific resistance per cubic inch.

$\frac{1}{\rho_1} = \varkappa$ = Specific conductivity per centimetre.

$\tau$ = Temperature gradient.

d = Diameter.

# ELECTRIC FURNACES
## IN THE IRON AND STEEL INDUSTRY

## *Part One*

### CHAPTER I

#### HISTORICAL REVIEW

GREAT interest is today manifested in electric steel and its production. Not only are the different iron and steel works installing electric furnaces or considering their adoption when enlargements become a good investment, but political economists are also carefully following the progress made in the electric-steel industry. The daily press frequently contains accounts *of the importance of electric iron and steel.* Considering the great and almost universal interest shown today in the new industry, it must seem astonishing that but ten years ago hardly a thought was given to the practical utilization of the electric furnace for producing steel. This remarkable growth originating in the laboratory seems to justify us in following the development of the electric furnace, and in tracing the causes which have made its entrance into the great industries possible.

In the first instance we must clearly understand that all electric furnaces are naturally apparatus in which electrical energy is consumed for the purpose of transforming it into heat. Their development on a large scale was therefore not possible until electrical engineering had succeeded in producing sources of current which furnished it economically, continuously and of sufficient size.

At the beginning of the last century thermopiles, or galvanic cells, as they are used today for operating house bells, or telephone

circuits, were the only sources of electric current at the disposal of the user of electricity, so that we see the electric current of this period confined in its application to the laboratories of the scientist. It was only toward the middle of the 19th century that a strong development started which has its foundation in Faraday's discovery of induction.

In 1831 Faraday found that each time he brought a strong magnet near to, or moved it away from, a coil of wire, the ends of which were separated a very small distance from each other, a tiny spark appeared at the point of interruption. We say, therefore, that Faraday found that the magnet induces a current in the electric conductor (the coil of wire).

This discovery brought a great light into the darkness which until then had covered the practical generation of electricity; for, hardly a year after Faraday's discovery, we find the first magnet-electric machine, which was built by Pixii. This was the first form of a dynamo machine, that is, of a machine which transforms rotary motion into electric energy. In Pixii's machine a coil of wire was arranged in the magnetic field of a strong ordinary horseshoe magnet, in such a way that when the coil was rotated, induced currents were produced, as discovered by Faraday. This first machine was soon followed by improved designs, which, even at this early period of electrical science in the fifties of the last century, were put to use in supplying light in lighthouses on the coasts of France and England.

The next step forward was accomplished by H. Wilde in 1866 in Manchester, by the construction of an electric machine, whose magnets were electro-magnets. For these a small machine with ordinary magnets furnished the current.

A Wilde generator of this type, which required about 3 h. p. for driving the exciting machine and about 15 h. p. for the main dynamo, was able to melt a bar of platinum 6 mm. thick (about ¼ inch) and 60 cm. (two feet) long.

The above mentioned electric magnetic machines were, however, despite their considerable power, unable to introduce electricity for general uses. An important forward step was still lacking until Werner von Siemens discovered the "dynamo

electric principle," which he laid before the Berlin Academy on January 17, 1867. According to this principle the "residual" magnetism that remains in even the softest iron is sufficient to produce an extremely weak current by which the magnetism can be strengthened more and more. The employment of this discovery in the construction of dynamos now made it possible to use electro-magnets instead of the ordinary permanent magnets heretofore used, and, with this improvement, we have the dynamo as it is today. It is used the world over, following the Siemens principle.

But even after Siemens' discovery considerable time elapsed before any great change occurred in the output of large electric generators. It was the invention of the incandescent lamp, first generally known in Europe through the Paris international electric exhibition in 1881, which brought about this development. Electrical power-houses in ever increasing numbers and sizes now appeared, and today we see them in nearly every city. If we finally call to mind the well-known first great power transmission of a current at 30,000 volts pressure over a distance of 170 km. (106 miles), between Lauffen and Frankfurt, Germany, which was shown to the world in 1891 at the time of the Frankfurt Exhibition, we find ourselves in the midst of tremendous advances of electrical science.

If we now turn to the history of the development of the electric furnace itself, we find its first traces at the beginning of the 19th century; that is, at the same time in which the sole means of producing electric currents was the thermopile, and at which time no thought of any electrical science existed. The first to consider the practical exploitation of electric energy by converting it into heat, probably was Davy, who, about 1810, during his experiments in the electrolysis of aluminum oxide, excluded any influx of heat from the outside, and produced the heat necessary for the experiment by the electric current itself, which he obtained from an apparatus naturally very inferior, from the view-point of our modern ideas. His apparatus consisted of a platinum plate connected with one pole of a thermopile of 1000 plates, the other pole being connected with an iron wire.

The latter projected from the upper side into a layer of clay carried by the platinum plate, which was in connection with the other pole. When the circuit was established the iron wire became white hot and melted where it was in contact with the clay.

A far more perfected arrangement was that of Pepys, who in 1815 welded an iron wire by heating it with an electric current. Pepys' apparatus can be looked upon as the first form of the

FIG. 1.

class of electric furnaces today known as resistance furnaces. A soft iron rod was slotted with a fine saw in the direction of its axis and the slot was filled with diamond dust. The rod was then wound with wire and heated to red heat for 6 minutes by means of an electric battery (Fig. 1). An examination of the iron wire showed that the diamond dust had disappeared, and that the iron had changed with the absorption of carbon. In this experiment iron was for the first time treated by the application of electric heat.

It is interesting to find that in 1843 A. Wall made the suggestion that pig iron be treated and converted by electrical means.

In 1853, 10 years later, we find in a French patent granted to Pichon, the first electro-thermic furnace. The patent claim is as follows: "economical and application of the electric light to metallurgy and particularly metallurgy of iron." The furnace reproduced by Fig. 2 shows the original design of a furnace indirectly heated by electric arcs. Such furnaces are used even today with some changes in the design given us by Stassano. The ore or metal which Pichon tried to melt in his furnace was dropped between electrodes of considerable area through which the electric current passed. It was expected

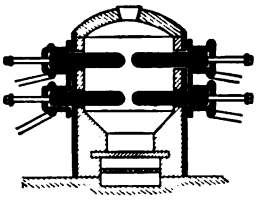


FIG. 2.

that the charge would melt under the influence of the temperature of the arc, and collect in the bottom, which in turn was to be heated. Pichon's idea was to build his type of furnace on a large scale, this being clearly indicated by the dimensions of the electrodes which were to be 3 m. (10 ft.) long and to have a cross-section of 60 sq. cm. (9.3 sq. inches).

It is interesting to observe that Pichon's suggestion appeared exactly at the time in which the first attempts were being made to illuminate the sea-coasts by means of electric light supplied by permanent magnet-electric dynamos. Electrical science, which thus called this furnace into existence, was, however, unable to further the realization of Pichon's daring plans, so capable of life as later developments show. The magnet-electric machine was by a large margin incapable of furnishing the current necessary for the operation of Pichon's furnace.

Many different schemes were tried, in the years immediately following Pichon, to utilize the electric current in the production of iron, but they failed, being in advance of their time. The English patents of William von Siemens, of the years 1878 and 1879, next bring developments in the design of electric furnaces. They contain nearly all the important details of the modern arc furnaces, and for this reason they will be examined somewhat more closely. Siemens used different types of furnaces. The first design consisted of a crucible surrounded by a metallic case, through the bottom of which projected one pole of an electric circuit. That part of the electrode in direct touch with the charge was provided with a point of platinum or other substance capable of resistance of great heat, in order to avoid contaminating the charge. The second electrode, which was connected with the other pole of the electric circuit, entered through the cover of the furnace and was cooled with water or other liquid. Figure 3 shows the arrangement of the furnace. Siemens later changed the design, making the electrode, which entered from the top, of carbon, while the lower metallic electrode was cooled with water. A heat-protecting

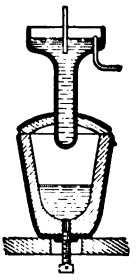


FIG. 3.

covering was provided for this furnace. The crucible was placed in a larger case of metal and the space between the two filled with charcoal or other poor conductor of heat, as shown in the design, Fig. 4.

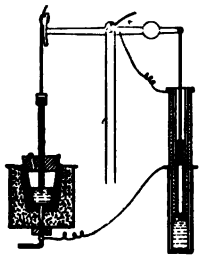


FIG. 4.

Siemens finally used a form of furnace very similar to that of Pichon. Two carbon electrodes were inserted in the sides of a crucible in such a position that they remained above the top of the charge, and the arc formed between them did not come in contact with the material to be melted. This furnace is shown in Fig. 5. With it Siemens succeeded in melting 10 kg. (22 lbs.) of steel per hour. He also reduced iron ore and fused metals of high melting point such as platinum, taking about one-quarter of an hour to liquefy 4 kg. (8.8 lbs.) of the latter substance. Siemens figured theoretically that the combustion of 1 kg. of coal under the boilers of a dynamo-electric generating plant would produce 1 kg. of melted steel.

Siemens' furnaces, in regard to their practical construction, attained a high degree of perfection. They were equipped with automatic devices for adjusting the carbons and to keep the arc length always the same. He also utilized the directive qualities of the electro-magnet in order to obtain the best heating effects. All modern constructions of arc furnaces are adaptations of this original design, differing simply in size and form and other minor respects. The reason why the Siemens furnace failed of successful introduction on a commercial scale, lies in the fact that current was still too expensive; it cost too much in those days to be of use in melting iron in electric furnaces.

FIG. 5.

With the suggestions of Siemens, the furnace subject seemed for the time exhausted. Aside from a long list of unimportant patents the ensuing time shows no progress until the appearance of the interesting patent of de Laval, of the year 1892. Fig. 6

shows this furnace. The hearth of a cylindrical furnace is divided into two parts by a bridge cooled with water. At the bottom of each of the two compartments metal or carbon electrodes are inserted and connected with a source of alternating

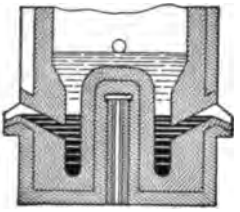


FIG. 6.

FIG. 7.

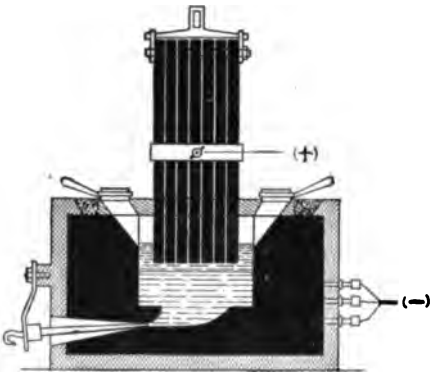



FIG. 8.

current. The furnace was to be charged from the top by removing the cover and first introducing a quantity of molten magnetic oxide of iron. The succeeding charges were to be of spongy iron.

In operating the furnace it was intended to cover the bridge with a layer of oxide or other fusible substance which would act as a resistance. With an iron-refining furnace oxidized iron was to be used. The object sought was to have the spongy iron undergo a refining process in falling through the material forming the resistance; and this was the purpose for which de Laval's furnace was designed. De Laval saw a great future for this furnace and the extent of his hopes can best be realized from the fact that with Nobel, in 1895, he laid plans for a power plant of some 35,000 h. p., to be used in melting iron by electricity. These bright hopes failed of realization, and de Laval's furnace has today an historical interest only, as the first example of a furnace to melt iron by direct resistance. But the plans show that we have arrived at an epoch in the development of electrochemistry, by aid of which, and that of great water-power it is possible to consider operating electric furnaces on a large scale.

Another type of resistance furnace, the Taussig, appeared in 1893. No longer is a separate liquid resistance required. The charge itself, whether metal or ore, forms the resistance, and in consequence the furnace takes the shape of a horizontal groove rather than a vertical one as Fig. 7 shows. This furnace also remained unused.

It is evident from the above that in the middle of the nineties of the last century there existed a number of designs for electric furnaces, and that the process of heating metal baths by electricity was well understood. But the iron industry had so far refused to take the electric furnace seriously. This is even more astonishing considering the pathfinding and successful employment of the Héroult furnaces of 1887 and 1888 in the aluminum industry, and the use of the electric furnace in the manufacture of calcium carbide in 1894. Both these industries had already attained their full growth when, with the new century at last, the interest of the iron industry in the electric furnace began to awaken. The main reasons for this late beginning of the electro-steel and electro-iron industries may be sought, first, in the high development of the existing process for the manufacture of steel and iron, which seemed to preclude any possibility of cheapening steel; and, second, in the fact that nothing definite was known about the quality of the product of the electric furnace.

The first practical constructions of furnaces to melt and refine iron appeared at the same places where the iron industry itself had come into being; that is, places having favorable water-power. Here the electric furnaces could obtain cheap current for experimental purposes. This leads to that point of the development which produced the present furnaces, to be considered more closely in later chapters; at this time, therefore, only the historical facts will be recorded in a general way.

In 1898 Stassano took out a patent in different countries claiming: "A method for the practical production of liquid wrought iron of any degree of carbon and of liquid alloys of iron by means of the electric current." Stassano's furnace under-

went many constructive alterations as a result of experiments made to obtain a practical apparatus, but his furnaces even as used today are based on the old principle of heating.

The next most important type of furnace used today, the Héroult, appeared in the years 1899 and 1900, and almost at the same time Kjellin with his induction furnace succeeded in producing an apparatus of practical use in the iron industry.

All these three furnaces were operated by electricity generated by means of water-power. The Stassano in upper Italy, the Héroult in Savoy, and the Kjellin in Sweden, and their practical success, first drew the interest of the iron industry. An important contributing factor also was a report by Dr. Haanel, chief of a commission of experts sent by the Canadian Government to Europe to study the electric furnace.

This report first brought together the different existing types of furnaces and considered them in their relation to each other. The plants of Gysinge, Kortfors, La Praz, Turin, and Livet were inspected, and it was found that a Kjellin furnace in Gysinge produced a superior quality of steel from raw materials consisting of charcoal iron and scrap iron. In Kortfors, and also in La Praz, the Héroult steel process was in operation, any desired quality of steel being produced by the method of first melting scrap and then refining it by the use of a large variety of slags. The Stassano furnace in Turin was not in operation at the time of the commission's inspection. In Livet a furnace by Keller, of a construction similar to that of Héroult, was busy melting iron direct from the ore.

From the above it is evident that in 1904, the time of the Canadian Commission's tour, the electro-steel industry had attained a healthy existence, at least where in proximity to water-power developments. The principal hindrance to the introduction of the electric furnace in the iron industry had now been overcome. In the production of steel the problem was to keep the iron from absorbing the carbon of the electrodes, and both Kjellin and Héroult successfully solved the difficulty although in different ways. Kjellin avoided the use of electrodes entirely, while Héroult brought the electric current into the furnace

through carbon electrodes, following the method used (for example) in the aluminum industry, where the electrolysis of the molten mass is desired. He, however, arranged his furnace so that there always remained a layer of slag interposed between the metal and the carbon, thus avoiding contact between the two.

Stassano sought to attain his goal in the reduction of iron directly from the ore and only later turned to the scrap-iron method. Hêroult and Kjellin were the first to regularly engage in the business of melting scrap iron in the electric furnace. And again it is Héroult to whom credit is due for the development of the art, to the end that from a charge of ordinary scrap any desired quality of steel may be obtained by refining it.

Improvements in the machinery for generating electric currents, especially in the design of gas engines of large capacity, had in the mean time opened the way for other cheap methods of producing electricity, so that the electro-steel industry was no longer limited to water-power locations. In 1905 there appeared the first such industry in Germany, in the works of Richard Lindenberg in Remscheid. The installation consisted in one Héroult furnace.

In the same year the Röchling Iron and Steel Works erected a Kjellin furnace and were the first to try the experiment of running an electric furnace in conjunction with a great iron establishment.

There remains to be mentioned that during this period the now much used Girod furnace appeared in a small way, and that the year 1906 was marked by the appearance of the Röchling-Rodenhauser furnace, of which the following chapters will speak more fully. With the latter there now existed an induction furnace by means of which (as also with the Héroult furnace) a superior steel of any desired quality could be obtained from a charge of any kind of raw material.

In recent years successful efforts have been made to produce iron by means of the electric-shaft furnace of Grönwall, Lindblad & Stalhane. More modern times have arrived and in the following chapters will be found a discussion of the present day furnaces as used in the electric-steel industry.

# CHAPTER II

## SOME FUNDAMENTAL LAWS AND TERMS OF ELECTRICAL ENGINEERING

BEFORE turning to a discussion of the different types of electric furnaces used today, it is necessary to have a clear understanding of some of the fundamental electrical laws and terms, for it is only through a knowledge of this, that an electric furnace can rightly be judged and a correct picture conceived of the occurring phenomena. In order to begin with the most important foundation for all electrical investigations we have first to deal with Ohm's law. This law says:

$$\text{Current} = \frac{\text{Drop in potential}}{\text{Resistance}}$$

or if $i$ denotes the current, $e$ the drop in volts and $r$ the resistance—

$$i = \frac{e}{r}$$

The resistance $r$ of a conductor is determined by the equation:

$$r = \frac{c\,l}{q}$$

where $l$ denotes the length and $q$ the cross-section of the conductor, while $c$ is a constant depending upon the material.

It can be shown, for instance, that under the same electrical conditions and measurements, a copper conductor will convey 5½ times the current that an iron conductor will. The reason underlying this is that evidently copper conducts electricity better than iron. We therefore speak of the different conductivities of different materials.

The above-mentioned phenomena may, however, be explained, since different materials give entirely different resistances, even though the dimensions may be the same. The resistance factor dependent on this material is called the "specific resistance"

and is mathematically indicated by $\rho$, so that the formula for the resistance of a conductor is,

$$r = c\frac{l}{q} \text{ and may now be written: } r = \rho\frac{l}{q}$$

The different conductivities are consequently the reciprocal values of the specific resistances.

In order to be able to apply our first law, the "ohmic law," we must clearly establish the electrical units. The current quantity is measured in Amperes, the potential or pressure in Volts, and the resistance in Ohms.

Originally the unit of resistance as established by Siemens consisted of a column of mercury one metre long and of one square millimetre cross-section at a temperature of 0° centigrade. In place of this resistance unit, we have the ohm to-day, which equals 1.063 Siemens units and corresponds to a mercury column 1.063 m. long, of 1 sq. mm. cross-section at 0° C.

The generally applied resistance unit, the ohm, was established in such a way that, with a pressure of one volt, and a resistance of one ohm, a current of one ampere resulted.

We now know what the dimensions of the mercury column are, and under which conditions it has a resistance of one ohm, and since the resistance of a conductor is,

$$r = \rho\frac{l}{q} \text{ where } \frac{l \text{ is in metres}}{q \text{ in square millimetres}}$$

we may calculate the specific resistance for mercury, which is

$$1 \text{ ohm} = \rho\frac{1.063 \text{ m.}}{1 \text{ sq. mm.}} \text{ or } \rho = 1 : 1.063 = .94073$$

In the above description of the resistance unit the temperature was always given. This was not done without having an object in view, for the specific resistance of a conductor is not only dependent on the material, but also on its temperature. Therefore, equal conductors at different temperatures have different resistances, and consequently with the same voltage they carry different currents.

The conditions governing the alterations of the specific resistance with changing temperatures have been established, by making exact measurements with the different materials. In a similar way the specific resistances were determined.

Concerning the changes in temperature, it was shown that the resistance of the metals and their alloys rose with increasing temperatures and in accordance with the following formula:

$$r_t = r_o (1 + \alpha t + \beta t^2)$$

where $r_o$ = the resistance at 0°

$r_t$ = the resistance at $t$°

$\alpha$ and $\beta$ are numerical constants, which have to be specially determined for each conductor.

For practical purposes when within moderate temperature differences, it will suffice if we use the following formula:

$$r_t = r_o (1 + \alpha t)$$

It is well known that the specific resistance of a metal depends so much on various substances mixed with it, that accurate figures, as they are known for the absolutely pure metal, have practically only a comparatively small value. It is sufficient therefore to figure practically with the following values:

| Material | $\rho$ |
|---|---|
| Copper | 1/55 |
| Brass, Iron, Platinum, Zinc | 1/10 |
| German Silver, and similar German Silver alloys: | |
| Monel metal | 1/4 to 1/2 |
| Carbon varies between | 100 and 1,000 |

The exact values of the specific resistances, and the temperature coefficients, are given for some of the materials which are used in the construction of electric furnaces. It is to be noted that the temperature coefficient for metals is positive, *i.e.*, with rising temperature its resistance increases. In contradistinction to this, carbon and non-metallic conductors are negative, *i.e.*, with rising temperatures the resistance is decreased.

| Material | $\rho$ at 15° C | $\alpha$ |
|---|---|---|
| Aluminum | .03 to .05 | +.0039 |
| Lead | .22 | +.0041 |
| Iron | .10 to .12 | +.0045 |
| Copper | .018 to .019 | +.0037 |
| Brass | .07 to .08 | +.0015 |
| German Silver | .15 to .36 | +.0002 to .0004 |
| Nickel | .15 | +.0037 |
| Platinum | .12 to .16 | +.0024 to .0035 |
| Silver | .016 to .018 | +.0034 to .0040 |
| Steel | .10 to .25 | +.0052 |
| Zinc | .06 | +.0042 |
| Carbon | 100 to 1000 | −.0003 to .0008 |

The temperature coefficients in the above table are only exactly accurate within comparatively small temperature intervals, in fact, are absolutely accurate only within the limits of 0 to 30° C. This is why the temperature coefficient only gives an approximate idea of the increase in the specific resistance. For instance, that which interests us the most is iron, with its growing temperatures. Unfortunately exact measurements of the resistance of iron at high temperatures are extremely difficult to make, and this is why we see so many contradictory statements concerning these. It is evident that the resistance of solid and also fluid iron varies with its chemical composition. To some extent a certain portion of the iron content will include gases and slag particles at the beginning of the run, and this causes it to have a higher resistance than it would have at the end of the heat, yet keeping the composition the same. But all of these influences are practically negligible; for in the many years' experience of the author in operating electric furnaces, there has never been any significant or practically real influence of the refining which could be credited to a change in the resistance of the iron. Thus the above-mentioned causes, which could theoretically call forth a change in the resistance, may be neglected in practise. We may now use the formulas and values which are sufficiently correct for practical purposes, and which are obtained by exact measurements for low temperatures. It

has been established that the specific resistance of ordinary basic bessemer iron at temperatures from 0° to 160° C., would change according to the following formulas:

$$\rho_t = .13\,(1 + 5 \times 10^{-3} t + 3.6 \times 10^{-6} t^2)$$

If in accordance with this formula we figure the value of $\rho_t$ for 1700°, we obtain

$$\rho_{1700} = 2.12$$

This result seems somewhat too high, as far as it can be judged with the operating values on hand which were obtained by the author, who has had the best results when figuring with a mean value of $\rho = 1.66$ when designing electric furnaces. *G I N* figured according to Neumann with a resistance of iron of .000175 ohm per cubic centimetre. This would correspond to a specific resistance of $\rho = 1.75$. This figure also shows that the result calculated above for the specific resistance of fluid iron is too high at 2.12. In this book $\rho = 1.66$ will always be used as the specific resistance of molten iron. Even though this value cannot lay claim to any theoretical accuracy, the calculations will, however, give results which correspond sufficiently with practical operating conditions.

It was remarked upon before that carbon, in contradistinction to the metals, has a negative temperature coefficient, so that with increasing temperatures the resistance of the carbon decreases. This phenomenon we have, however, in a much more extraordinary measure, with the so-called "conductors of the second class." Under this heading we mean materials, or bodies, which at ordinary temperatures have practically no conductivity, or at least so small a one as not to be worthy of consideration. With increasing temperatures these conductors of the second class attain steadily bettering conductivities, so that they can eventually be used as conductors directly. We shall have to deal with conductors of the second class in detail, when discussing the various furnace types. It may be well here to speak of the well-known application of a conductor of the second class, in the form of the filament or glower of the

*Nernst* lamp, which consists of porcelain and magnesia, which substances are non-conductors at ordinary temperatures. The glower of the Nernst lamp must therefore be warmed up first, before it is in any way capable of taking up the lighting current. This pre-heating was at first accomplished with the heat of an ordinary match, whereas it is to-day done electrically. All substances which are used for fire-resisting materials for the lining of electric furnaces, are similar in a way to the filament of a Nernst lamp, *i.e.*, all constructional material for the hearth or roof becomes a more or less good conductor, at the high temperatures which are prevalent in electric furnaces, and this is, of course, taken into consideration in their construction, as will be made evident later on.

The constructional material used most, for the lining of electric furnaces, is dolomite or magnesite, aside from the protecting brickwork used as a backing, and aside from the roof material. This material is mixed with tar and pressed into bricks, which are later on used in the furnace hearth, or it is directly tamped into the furnace. The furnace walls produced in this way have a small conductivity in their cold state, so that in such a case they may be regarded as non-conductors. They lose their resistance with increasing temperatures very fast, as is shown in Fig. 9, which shows the results of an investigation, in graphic form, of the resistance measurements of magnesite and tar rods, in relation to the temperature. The curve shows plainly how the specific resistance suddenly falls. This is designated by $\rho$ in the figure. It also gives a characteristic picture of the conductivity conditions, as they appear with conductors of the second class. We will recur to this matter again in due course.

As we have already dealt with the prime laws of all electrical calculations, we will now deal briefly with the possibilities of different connections. This leads us to the *series* and *parallel* connections. Both connections will again be met in the detailed description of electric furnaces. As both have their advantages and disadvantages, it seems well that the prime difference be clearly stated.

We will therefore again recur to the analogy between electricity and water. Let us suppose we had a water-power of very high fall but of comparatively very little water, and that several water-wheels were to be driven with it. If the wheels could be operated at any place it would be best, with the small

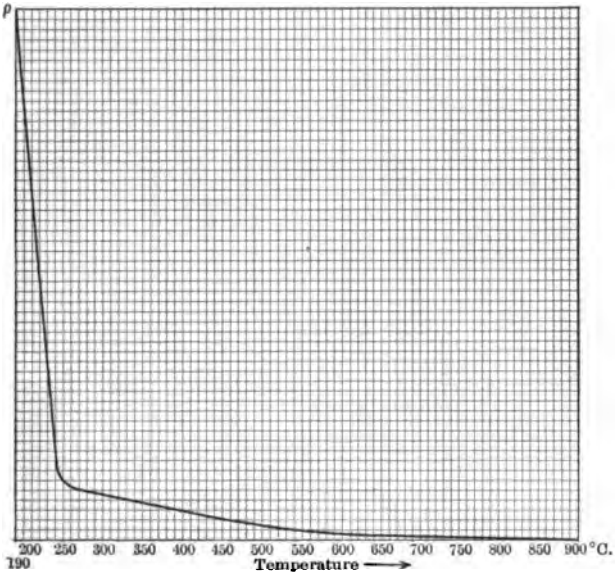



FIG. 9.

amount of water available, that it be used time and again, or sausage-like in series, through the different wheels. That is to say, the water-wheels could be arranged at different elevations of the fall, and thus by dividing the pressure an equal amount of water could be used to drive each wheel. The small amount of water is similar to a small current, the high fall or great difference in pressure is similar to a high voltage. In such a case if the current present can be used in the electric apparatus installed, but only a portion of the prevalent voltage is required, then the apparatus utilizing the current can be so made, that it only absorbs a portion of the voltage. In this case, therefore, the same current and same amperage flows through the various apparatus using it, and we consequently speak of a "series connection."

We may, however, also conceive of a case where a water-fall consists of a considerable quantity of water, but has only a small pressure. A well-known case is on the Mississippi River at Keokuk, where eventually 230,000 HP, at 25 cycles, 3-phase current will be generated. Here it would be practically impossible to use this immense volume of water in one turbine. We are therefore obliged to separate these large volumes of water where each part materially has the same fall, between the intake and the tail-race. We have here then a case where several turbines are arranged next to each other. This case also has its simile in electrical engineering, the best known case being perhaps the ordinary incandescent lamp, where the circuit is also so arranged that only a small part of the main current flows through each lamp, at the same voltage for each. There may be any number of lamps next to each other, or as we say, they receive their current in *parallel*.

Both cases are used in electric-furnace constructions. The Héroult furnace is an example of a series connection, while the Girod furnace employs a parallel connection.

These furnaces are described later on, but a few words here concerning their method of connections will not be amiss. Figure 10 shows the schematic wiring diagram of a Héroult furnace, while Fig. 11 shows the main features of the connection in a Girod furnace. It is evident, that in Fig. 10, the current would flow through first one and then the other conductor, whereas in Fig. 11 the two points of the circuit are connected together by means of two conductors connected in parallel. Of course Ohm's law is applicable in both cases. Accordingly with a resistance of $r$ in the conductor and having a voltage $e$ between its terminals, we would have a current of $i = \frac{e}{r}$ amperes. If the voltage $e$, in Fig. 11, is prevalent between the points $A$ and $B$, Ohm's law will, of course, hold for each parallel connected conductor.

Suppose that between the points $A$ and $B$, we have the voltage $e$ and between these points we also have the resistances $r_1$ and $r_2$, the resultant current being $i_1$ and $i_2$, respectively.

Then in a similar way as with the water-wheels, the main current will be equal to the sum of its parts, *i.e.*, $i = i_1 + i_2$. We therefore have the first of *Kirchhoff's* laws: "*At each point of division the sum of all the incoming currents equals the sum of all the outgoing currents, or at each point of division the sum of all currents equals zero.*" With this it is assumed that the incoming currents are regarded as positive and the outgoing as negative currents.

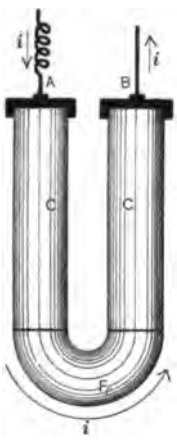



FIG. 10.

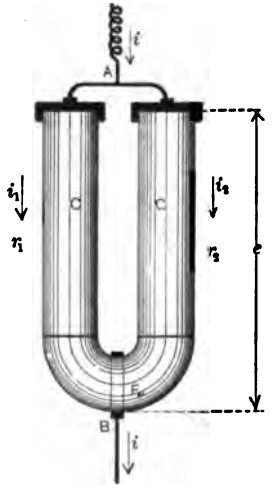



FIG. 11.

From Fig. 11 it follows that, $i_1 = \frac{e}{r_1}$ and $i_2 = \frac{e}{r_2}$ or $e = i_1 r_1$ and $e = i_2 r_2$. From this it follows that $i_1 \times r_1 = i_2 \times r_2$ or we have the proportion $i_1 : i_2 :: r_2 : r_1$, *i.e.*, currents *which flow parallel to each other vary inversely as the resistances of the parallel connected conductors.*"

We will now investigate how large the combined resistance becomes, *i.e.*, the resistance which is there, when both the parallel connected conductors $r_1$ and $r_2$ are opposed to the current flowing.

In order to answer this question, suppose the two parallel connected conductors to be replaced by a single conductor, having the same combined resistance $r$. This would not change

the current conditions, and with the voltage $e$ between $A$ and $B$ remaining the same, we would also have the total current $i$ remaining, so that, $i = \frac{e}{r}$ as before.

As demonstrated before $i = i_1 + i_2$. If we substitute for these current volumes their corresponding voltage and resistance equivalents we have:

$$\left\{\begin{array}{l} i = \frac{e}{r} \\ i_1 = \frac{e}{r_1} \\ i_2 = \frac{e}{r_2} \end{array}\right\} \text{ consequently } \frac{e}{r} = \frac{e}{r_1} + \frac{e}{r_2} \text{ or } \frac{1}{r} = \frac{1}{r_1} + \frac{1}{r_2}$$

This gives the size of the combined resistance.

$$r = \frac{r_1 \times r_2}{r_1 + r_2}$$

In the same way this rule also holds for $n$ parallel connected circuits. Designating the combined resistances again by $r$, we have,

$$\frac{1}{r} = \frac{1}{r_1} + \frac{1}{r_2} + \frac{1}{r_3} + \ldots . \frac{1}{n}.$$

As the reciprocal of the resistance is designated as the conductivity, we may define this equation by:

"*The conductivity of a combination of conductors is equal to the sum of the conductivities of the single conductors.*"

If the $n$ conductors are equal to each other, then

$$\frac{1}{r} = \frac{1}{r_1} + \frac{1}{r_1} + \frac{1}{r_1} + \ldots . + \frac{1}{r_1} = \frac{n}{r_1} \text{ or } r = \frac{r_1}{n}$$

*i.e.*, "*The combined resistance, of* n *parallel connected resistances, equal to each other, is equal to the* n*th part of any single resistance.*"

In accordance with the above, it is now possible to give an arithmetical example of electric-circuit conditions, as they are often found with electric furnaces.

The circuit is to consist of two carbon blocks or electrodes in touch with a connecting iron block. The carbons and the iron may have equal cross-sections, and may be round of, say, 350 mm. diameter (about 14 inches). The length of each carbon block is to be 1.5 metres (about 60 inches), and the length of the iron block 1 metre (about 40 inches).

In calculating the resistance of each part of the circuit we know that $r = \rho \times \frac{l}{q}$. In glancing at Fig. 12, we may take the circuit as consisting of two equal parts, which are connected in series in the first place, and in parallel in the second case. The resistance $r'$, as shown by the figure, is composed of the resistance $r_c$ of the carbon block, and the resistance $r_{Fe}$ or half of the iron block.

Consequently,

$$r_c = \rho_c \frac{l_c}{q_c} = 500 \frac{1.5}{350^2 \frac{\pi}{4}} = .00779 \text{ ohm.}$$

(Here the average value for $\rho_c$ is taken from the table on page 14, where the specific resistances of carbon are given.)

$$r_{Fe} = \rho_{Fe} \frac{l_{Fe}}{q_{Fe}} = .11 \frac{.50}{350^2 \frac{\pi}{4}} = .000000572 \text{ ohm.}$$

Here the average value for $\rho_{Fe}$ was also taken from the table.

FIG. 12.

Even this short example shows how very small the iron resistance is compared with the carbon. For even were the carbon and iron, in the above example, of equal lengths, the iron resistance value would have risen to three times the value given $\left(= \frac{1.5}{.500}\right)$, but even so the carbon would still have a resistance 2,500 times as great as that of iron, and this is entirely on account of the extraordinary differences in their specific resistances.

Turning again to the example, we find that we know the resistance of the parts of which the circuit is composed. It is

$$r' = r_c + r_{Fe} = .007790572 \text{ ohm.}$$

In case of a series connection the current would have to traverse this resistance twice, so that this resistance would be.

$$r_H = 2\,r' = 2 \times .00779 = .01558 \text{ ohm.}$$

In the second case, *i.e.*, with a parallel connection, we have a total resistance composed of a combined resistance, consisting of two similarly constituted parts, each having a resistance of

$$r' = r_c + r_{Fe} = .007790572 \text{ ohm.}$$

As the combination resistances are alike and in parallel, we have $n = 2$ for the above case, or

$$r_P = \frac{r'}{2} = .003895 + \text{ohm.}$$

It is evident, therefore, with the same conductor under the same conditions, but in the first case having been in series, and in the other case connected in parallel, that the series connection has four times the resistance of the parallel connection.

This extraordinarily different resistance of the two connections is, of course, not without its influence on the current and voltage conditions. This is evident from Ohm's law, where $i = \frac{e}{r}$ and the example before us with equal voltages gives us four times the current with the parallel connection, as it does with the series connection. Or as $e = i\,r$, and if we wanted equal currents in both cases, we would have to have four times the voltage in the case of the series connections, compared to the parallel arrangement of conductors.

It may be well to mention here, that the above example only holds for arc furnaces, with series or parallel connected electrodes, when the electrode measurements are alike, as they were assumed to be in the example.

*What action is there then, when an electric current flows through a conductor?* It has always been evident in order that the current may flow through a conductor that a definite voltage was necessary, in order to overcome the resistance. Consequently, when an electric current flows through any conductor a

certain *work* is accomplished, which must come to the surface in one form or another. In our case, we find work produced by the current, showing in the conductor again as heat. In what degree this heat is developed, is given us by Joule's law. This was established by the English physicist Joule, and experimentally determined by him. It is as follows:

"*The heat developed by a current flowing through a conductor, is directly proportional to the time, proportional to the resistance and proportional to the square of the current,*" or $Q = C\ i^2\ rt$, where

$Q$ = the heat generated
$t$ = the time the current is flowing
$i$ = strength of the current
$r$ = the resistance
and $C$ = a constant dependent on the units chosen.

If the current $i$ is measured in amperes, the potential $e$ in volts and the time $t$ in seconds, then $C = .24$, which has been determined by most accurate measurements. Therefore

$Q = .24\ i^2 r\ t$ gram calories or, as according to Ohm's law
$e = i\ r$, we have
$Q = .24\ eit$ gram calories.

If the heat is to be measured in kilogram calories, it is to be noted that 1 Kg. calorie = 1000 gram calories, so that the right side of our equation is to be divided by 1000.

If the work produced is not to be expressed in kilogram calories, but in metre kilograms (or the equivalent of the foot lb.), we find that 1 Kg. calorie = 424.7 metre kilograms. If the work delivered be designated by $A$, we have

$$A = \frac{.24\ eit}{1000}\ 424.7 = .1019\ eit \text{ m. kg.}$$

now $.1019 = \frac{1}{9.81}$ *i.e.*, it is equal to the reciprocal of acceleration, consequently

$$A = \frac{eit}{9.81} \text{ metre kilograms.}$$

We usually denote the *work delivered in one second as effect* or *power*, and have chosen $p$ to denote it, hence,

$$p = \frac{e\,i\,t}{9.81} \text{ metre kilograms.}$$

With electrical measurements we do not desire to determine the effect in kilogram metres, but in *volts* × *ampers*, or in short *voltampers*, otherwise known as *watts*, while the work in *joules* = .24 *eit*, or as *eit* is measured in *watt-seconds*, *watt-hours* or *kilo-watt-hours*, all in accordance with the measurement of time, be it in seconds or hours, and whether the power is to be inserted in watts or kilowatts. Thereby 1 kilowatt = 1000 watts.

For the conversion of *metric horse-power* into watts, the following are determining factors:

1 HP metric = 75 kg. m.; as the electric power

$$p = \frac{e\,i}{9.81} \text{ in kg.} = ei \text{ watt}$$

*i.e.*, 1 m. kg. = 9.81 watt, consequently 1 HP = 75 m. kg. = 75 × 9.81 watt = 736 watts.[1]

This gives the relation between the mechanical and electrical units. If we arrange the determined factors in the form of a table, we obtain the following:

The heat generated in a conductor by a current is,

$Q$ = .24 *eit* gram calories

= .24 $i^2$ *rt* gram calories

where $e$ is to be inserted in volts

$i$ is in amperes

$r$ is in ohms

$t$ is in seconds.

The power, or the effect is

$p$ = $ei$ watt or volt amperes

= $i^2 r$ watt.

[1] One British HP = 33,000 ft. lb. = 746 watts.

Here 1 kilowatt = 1000 watts

$$= 101.98 \frac{\text{m. kg.}}{\text{seconds}} = 1.360 \text{ HP}$$

$$1 \text{ m. kg.} = 9.806 \text{ watt} = \frac{1}{75} \frac{\text{m. kg.}}{\text{seconds}}$$

$$1 \text{ HP} = 736 \text{ watts} = 75 \frac{\text{m. kg.}}{\text{seconds}}$$

The delivered work is given by the formula,

$A = eit$ watt-seconds or joules

$= i^2 rt$ watt-seconds or joules

Here 1 watt-second = .24 gram calories = 1 joule
= .10198 m. kg.

1 watt-hour = 3600 joules = 864.5 gram calories
= 367.1 m. kg.

1 kilowatt-hour = 1000 watt-hours
= 864.5 kilogram calories
= 367114 m. kg.

1 m. kg. = 2.35 gram calories
= 9.806 watt-seconds.

# CHAPTER III

## EFFECTS OF THE ELECTRIC CURRENT

THE effects of the electric current which interest us most, are its heating effects. Let us therefore consider what possibilities electrical engineering offers for the production of heat.

### 1. DIRECT HEATING BY RESISTANCE

In the foregoing chapter we have seen that when an electric current flows through a conductor, heat is developed and the quantity produced is

$$Q = .24\ eit \text{ gram calories}$$
$$= .24\ i^2\ rt \text{ gram calories.}$$

If we for example force an electric current through an iron conductor the temperature of this conductor will increase. The heating will therefore be greater and more rapid with increasing current and increasing resistance of the iron conductor. Possible methods for making this resistance larger become evident from a glance at the formula recently mentioned which reads:

$$r = \rho \frac{l}{q}$$

An increase of resistance occurs if the cross-section is reduced, or if the length of the iron conductor or the liquid metal bath is increased.

The method of heating thus explained may be called *direct heating by resistance* for the heating is affected solely by the inherent resistance of the metal to be heated.

The *Taussig* furnace, mentioned in Chapter I, is an example of an electric furnace built on this principle.

When we consider that the direct heat by resistance is not confined to the metal it is desired to heat and that any such method of heating must also naturally cause heat to appear in every wire used to conduct the electric current, we encounter the first difficulty which operates against a practical utilization

of the direct heat by resistance for the purpose of heating metal baths. An iron bath is a comparatively favorable condition at that, for the resistance being $r = \rho \frac{l}{q}$ the specific resistance $\rho$ is of considerable importance in creating the higher degree of heat. This point is, of course, carefully considered in electrical engineering and it is for this reason primarily that copper is used for electrical circuits. Copper by virtue of its small specific *resistance* ($\rho$ = .018 to .019) is one of the best conductors for the transmission of heavy currents, for it permits the use of relatively small cross-sections without attaining too high a temperature. In contrast thereto the specific resistance of iron, for example ($\rho$ = .1 to .12), would be the deciding factor from the standpoint of heat loss, and with equal cross-sections for copper and iron we would have a greater heat in the latter in the proportion of .1 to .018.

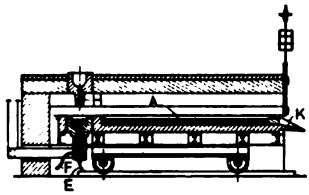


FIG. 13.

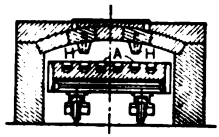


FIG. 14.

With equal cross-sections for iron and copper, and equal lengths of the conductors, iron will attain a considerably higher temperature. Especially as its heat will be further increased by the fact that the metal in the heat protective covering of the electric furnace will rise to higher temperatures by reason of its positive heat coefficient, which in turn adds to its resistance. Yet the fact still remains that the specific resistance of iron must be placed as being very low. With a system of pure resistance heating and with a resistor of iron, exceedingly high current strengths would be required to produce the temperatures needed in electric furnaces, and the currents would have to be exceedingly strong even if the cross-section of its iron resistor should be made very great

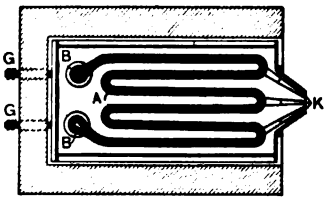


FIG. 15.

and the furnace bath cross-section very small in order to increase the resistance as much as possible.

An example will serve to illustrate more clearly the conditions of this kind of electric furnace employing direct heat resistance.

Suppose we assume that by means of pure resistance heating, a fluid iron bath of one ton is to be supplied with 200 kw. In this case the heat would be generated only by the current overcoming the resistance of the bath. This is the amount of energy with which an electric furnace of 1-ton capacity would normally be operated. In order to make the iron bath of as large a resistance as possible, the molten iron is to be contained in a long channel of the smallest practicable cross-section. A furnace of this kind having a long narrow channel has also been patented by *GIN*. Figs. 13, 14 and 15 show views of this furnace, respectively longitudinal cross-section, vertical cross-section and a plan view. We might use this arrangement as an example. The size of cross-section has been taken as 10 cm. (4 inches) high and 5 cm. (2 inches) wide. This has been done in order not to reduce the channel cross-section to such a degree, that the furnace would be rendered inoperative. Or if the cross-section were made much smaller, the cooling surface would become extraordinarily large, and thus cause very large losses. This would be entirely independent of the metallurgical difficulties which would ensue if any slagging work were attempted in the narrow channels. The size channel chosen therefore would still be practically workable.

The following assumptions are therefore made for this example:

| | |
|---|---|
| Capacity of furnace | 1 ton = (1,000 Kg.) |
| Energy consumption | $A$ = 200 kw. |
| Cross-section of bath | $q$ = 5,000 sq. m.m. |
| Specific gravity of molten iron, about | 7.0 |
| Specific resistance $\rho$ of molten iron, about | 1.66 |

From this it follows that:

$$\text{Volume of iron} = \frac{1000}{7} = 142.8 \text{ cu. decimetres.}$$

Length of the iron column $L = \frac{142.8}{.5} = 285.6$ d.c.m. = 28.5 metres = about 94 ft.

Hence the resistance would be:

$$r = \rho \times \frac{l}{q} = 1.66 \times \frac{28.5}{5000} = .00946 \text{ ohm.}$$

As the Joule effect $A = i^2 r$, we have

$$i = \sqrt{\frac{A}{r}} = \sqrt{\frac{200000}{.00946}} = 4598 \text{ amperes.}$$

It is evident therefore that a very considerable current would have to be supplied. This also means large copper cables for bringing the current to the furnace, as those of inadequate cross-section would heat up too much.

The following table shows the currents usually permitted in wires and cables:

| Area | | Carrying Capacities | |
|---|---|---|---|
| Circular Mils. ($d^2$) 1 Mil. = .001 Inch | Square Mils. ($d^2 \times .7854$) | Rubber Insulations Amperes | Other Insulations Amperes |
| 4106. | 3225. | 12. | 16. |
| 6529. | 5128. | 17. | 23. |
| 10381. | 8153. | 24. | 33. |
| 16509. | 12960. | 33. | 46. |
| 26250. | 20617. | 46. | 65. |
| 41742. | 32784. | 65. | 92. |
| 66373. | 52130. | 90. | 131. |
| 83694. | 65733. | 107. | 156. |
| 105538. | 82887. | 127. | 185. |
| 133079. | 104520. | 150. | 220. |
| 167805. | 131790. | 177. | 262. |
| 211600. | 166190. | 210. | 312. |
| 250000. | 196000. | 275. | 412. |
| 400000. | 313900. | 330. | 500. |
| 500000. | 392000. | 390. | 590. |
| 600000. | 471000. | 450. | 680. |
| 700000. | 549500. | 500. | 760. |
| 800000. | 628000. | 550. | 840. |
| 1000000. | 785400. | 650. | 1000. |

The above table is for insulated wires, whereas bare conductors may carry higher current densities.

If in the previous example for the 1-ton furnace we allow a current density of 1.5 amperes per square millimetre (about 1000 amperes per sq. inch), the secondary conductors leading directly to the furnace would have a cross-section of

$$\frac{4598}{1.5} = 3065 \text{ sq. mm. (about 4.75 sq. inches).}$$

This would entail $.3065 \times 10 \times 8.9 = 27.28$ kg. of copper per meter length (or about 19.5 lbs. per foot length).

Even this value shows that the leads for furnaces of the simple resistance type become extraordinarily expensive, and this is especially so for furnaces of larger capacities.

The voltage necessary to force the required current through the iron bath of the 1-ton furnace is

$$e = ir = 4598 \times .00946 = 43.5 \text{ volts.}$$

These give us the entire range of electrical conditions, but these must be considered primarily for direct current. When operating electric furnaces for alternating current, there would be certain deviations, which will not be taken into consideration, as direct current gives simpler equations, so that the above calculations are quite sufficient for the case before us.

Considering the above circumstances, we may now establish the following:

*Characteristic marks of electric furnaces having direct resistance heating.*

**a. Concerning the Electric Characteristics**

As the heating occurs by means of the current passing through, and overcoming the resistance of the iron bath, it is entirely uniform at all places.

Furthermore as the heat generated is proportional to the square of the current, the smallest changes in the temperature may be brought about by altering the voltage of the furnace. Such changes would be absolutely uniform throughout the entire bath. In this way by choosing high enough voltages, the

highest temperature may be reached. Besides this the following may be noted:

As the iron has a comparatively low specific resistance only at the high temperatures prevalent in liquid iron baths, it follows that direct resistance heating may only be accomplished by applying very heavy currents. For the same reason the voltages required for the operation of these furnaces are comparatively low.

The high currents have the disadvantage of demanding expensive cable installations, whereas the low voltage has the advantage of simpler and easier insulation, and the advantage of eliminating all danger which might befall the furnace attendants.

The high currents can only be decreased by correspondingly increasing the voltage and contracting the bath cross-section, or by increasing the length of the bath.

This brings us to:

### b. The Metallurgical Characteristics

Primarily the good points here are the uniform heating, and the easy regulation within narrow limits at any desired high temperature.

The disadvantages are:

To obtain good electrical conditions it is necessary to use long channels having small cross-section which means large cooling surfaces. This is equivalent to high thermal losses which must be covered by expensive electrical energy—consequently making the power-consumption figures very high.

It seems that a regular operation of metallurgical process is precluded, as the working with slag and moreover the changing of slag would almost offer practically unsurmountable obstacles in the line channels. A uniform composition of the furnace contents would hence be unattainable. A lasting durability of the furnace refractories also seems practically unobtainable, considering that the refractory walls between the channels are attacked from both sides by molten iron.

This direct resistance furnace, with its channels running to

and fro, still fails in spite of several electrical advantages. Practical operation has also shown this. For the one furnace of *GIN* built as here described, was an utter failure. Even so, we see patent applications today of similar ideas, which are to be discarded, as they are bound to be unsuccessful owing to the same inherent weaknesses.

These direct resistance furnaces, as just described can therefore not be considered for practical operation in the iron and steel industry.

### 2. INDUCTION HEATING

If we are able to circumvent the difficulties of leading very heavy currents to the iron bath, we may decrease the resistance of the bath at will if we can only increase the current strength to correspond. This would then allow us to use furnaces with large and wide hearths such as the metallurgist must necessarily demand.

The solution of the problem is found in the furnace type known as induction furnaces, which may also be called furnaces with resistance heating. These have the good points of resistance heating with the current being caused by induction, without bringing with them the disadvantage, just mentioned above, of the current having to be led to the furnace with immense conductors. This is what has enabled these furnaces to attain their great practical importance.

On this account induction furnaces are discussed at length in the tenth and following chapters. It suffices to say here, that the induction furnace belongs to that group having a type of direct resistance heating.

### 3. INDIRECT RESISTANCE HEATING

We shall designate all furnaces as resistance furnaces with indirect heating in which the iron itself is not the important resisting element but rather some other conductor of very low conductivity.

This conductor, that is the actual heat resisting element, is placed into the circuit and heated so that it can give up the heat generated in it, to the material to be heated.

As we can now choose for the heat resisting body, a material having a very high specific resistance, the extremely heavy currents are no longer required, which were necessary for the direct resistance heating of molten iron. Consequently cable installation will be less expensive.

Such furnaces with indirect heating are often used in laboratories. We have for instance the type suggested by BORCHERS. (See Fig. 16.) This has carbon blocks or rods of large cross-section which serve as terminals between which a carbon rod of very small cross-section is clamped, which serves as the heating resistance or resistor. The material to be heated is heaped about the small carbon rod. Thus while the current is flowing, the carbon rod heats the desired material indirectly.

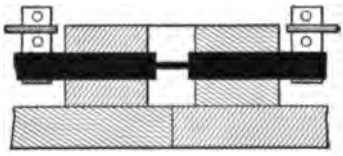


FIG. 16.

In practice we find furnaces with similar indirect heating, but they are used mainly for the manufacture of Carborundum. Here we find that a tamped-in mass of powdered coke acts as the heat resisting material.

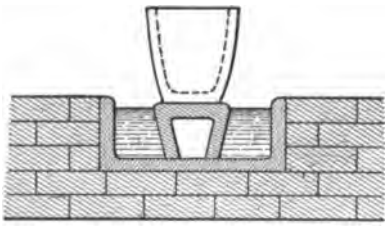


FIG. 17.

Such designs are not used in the practical manufacture of iron, where the charge to be heated comes in direct contact with the heating element, where the latter is usually of carbon. For it is well known that iron absorbs carbon readily until it is finally saturated with it. It is consequently impossible to use carbon as the heating element, not only because the carbon brings impurities to the iron, but primarily because the carbon resistance would be worn away in the shortest time by the iron. In place of carbon we could suggest the utilization of a conductor of the second class as the heating element. This could be of the same material as the furnace lining which surrounds the metal bath; such as dolomite

or magnesite held together with anhydrous tar as binding material.

If we were to place such a heating element or resistor in an iron bath we would have two parallel circuits for the current. In this case a very poor conductor (the heating element) of very high resistance would be in parallel with a very good conductor of very low resistance (the iron). As the currents in parallel circuits are inversely proportional to the resistances practically all of the current would flow through the iron while the conductor of the second class would almost be without current.

Hence it is established *that it is impracticable for any iron process for furnaces having indirect resistance heating, to have the heating element in parallel with the iron to be heated.*

Another possibility of indirect heating could be obtained by utilizing the walls of a vessel, such as a crucible, by heating it with an electric current either directly or indirectly. One of the best known of these furnace types is the *HERÄUS* laboratory furnace, where the heating chamber is composed of a cylindrical tube, into which small crucibles may be placed. The tube of refractory material is wound with a spiral of platinum wire or ribbon, which is placed in the electrical circuit, and thus its heat is transmitted to the furnace chamber.

Similar methods, however, have been proposed for several iron processes, one of these being by *GIROD*. Accordingly several crucibles were placed in retorts composed of fire-brick, the bottoms of which were composed of suitable resistances, as shown by Fig. 17. In order not to imperil the retort walls by the heat, various resistances were used for the bottom material. The resistance material itself consisted of carbon and silica. With a furnace of this kind utilizing indirect heating, a temperature of 1400 to 1700° C. was reached. When the cross-section of the heating element was reduced, as shown in the sketch, temperatures as high as 2000° C. were attained.

In these furnaces, which *GIROD* used principally for making ferro-alloys, he also melted steel. This necessitated 1440 Kw.-hrs. per ton melted.

In the above we have an electric furnace which differs only

from the ordinary crucible by the electrical heating. Even if these have several advantages, the *GIROD crucible furnace* still has the disadvantages of the small size of the common crucible, the difficulty of obtaining a complete uniformity from a greater number of crucibles, the high cost of the crucibles, and, compared to other furnaces, a very high power consumption.

All these are reasons why these furnaces have not found a place in the iron industries. This furnace construction had to be mentioned here, in order to give as complete a picture as possible of the various electrical heating possibilities.

FIG. 18.

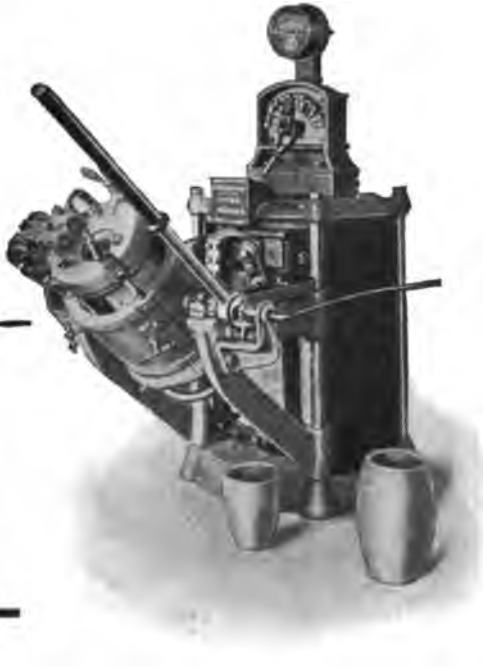


FIG. 18*a*.

We still have to mention another indirect heating method, where the walls of the heating chamber are the heating elements themselves, and consequently carry the current. One of these designs is the *Helberger furnace*. This consists, as Fig. 18 shows, of a crucible, which is placed in circuit by means of carbon contacts, so that the current passes vertically

through the crucible walls. Helberger uses the ordinary carbon or graphite crucibles.

Before using these crucibles they are prepared by a patented process which permits the current passage through the crucible walls only. These furnaces were originally built only for the handling of precious metals. As communicated by the firm of Hugo Helberger, the current conduction from the crucible wall to the metal contents was made more difficult by removing the graphite from the inner surface of the crucible. This graphite removal is accomplished by blowing air into the red-hot crucible. As long as the material is not molten there is no passage of the current. As soon as the contents becomes fluid, it gets into intimate contact with the red-hot lining, which acts as a Nernst filament would, so that some electrical energy also goes through the lining and directly through the bath. This action has no deleterious influence on the charge, as the metal for which these small furnaces are applicable is tapped as soon as it is molten, for a refining of the charge is not necessary or desired.

If these furnaces are to be used in steel works for small trial melts, for which they seem excellent, carbon crucibles are used which are nearly always lined with a metal oxide from .4 to 1.2 inches (10 to 30 mm.) thick. These carbon crucibles, so the inventor advises, need only half the voltage of the graphite crucibles, a result of this being that the deviation from the normal working current is not so great, so that in this way it is possible to practically lead the current entirely through the walls of the crucible.

The practical design of this furnace is therefore to be regarded as having been well done. The crucible is built together with a regulating transformer, as shown by Fig. 18*a*. The upper carbon contact covers the heating chamber at the rim only, so that the process going on in the crucible may easily be observed. The crucible is protected against radiation by a fire-brick cylinder. The clamping arrangements holding the carbon contacts are water-cooled. The size of the Helberger furnace is limited on account of the difficulty encountered when manufacturing larger crucibles. Yet, the manufacturers, The Helberger Co., of

Munich, Germany, state that furnaces, up to a capacity of 300 Kg. (660 lbs.), are being successfully built to-day.

### 4. ARC HEATING

When counting the various possible ways of heating we must not forget to mention the electric arc for this has found the widest application in the iron industry. We will spend much time in the following chapters, therefore, with arc heating and arc furnaces. They are mentioned here only for the sake of completeness.

### CHEMICAL ACTION

Besides the purely thermal action of the electric current the mill man will also be interested in the chemical action which takes place when an electric current is passed through a liquid. The best known example of this is the disassociation of water into its constituents, oxygen and hydrogen. This may be observed by passing a direct or continuous current through water. In so doing the well-known reaction takes place as oxygen is given off at the positive pole and hydrogen at the negative pole.

To this belongs also the best known electro metallurgical application of electrolytic action for the smelting of aluminum. According to the method first proposed by Héroult, the clay is melted by the action of arc heating, and simultaneously the molten mass is separated electrolytically in such a way that the aluminum is freed and collected at the negative pole, whereas at the hanging positive carbon electrode the oxygen is set free, and, together with the carbon of the electrode, escapes as carbonic acid gas.

These examples are sufficient to show how chemical action may be brought about by the electric current. In this instance it is to be observed that this action only occurs when direct current flows through the electrolyte to be separated. If on the other hand alternating current is used, where the current direction is constantly changing, then no electrolytic action can take place. For supposing we had an apparatus for the dissociation of water, which was supplied with alternating instead of continuous current.

Then during one moment with the current in one direction, we would obtain oxygen at the electrode, and during the next moment with the reversed current direction we would receive hydrogen. It is evident, therefore, that electrolytic effects do not arise when alternating current is used.

From this it also follows that molten iron masses of electric furnaces, through which current passes, are not subject to any chemical action as long as alternating current is used. We could in any event, as in the above example, assume a momentary chemical action, which however would be reversed in the next moment, for even though it appears momentarily, it does not come into play as far as the metallurgical process is concerned. This assumes that the reversal of the chemical effect is not interrupted.

When using direct current in iron baths, electrolytic action naturally occurs, by which iron sulphides and iron phosphides may be separated. These suggestions have also found their way into the patent office.

Electrolytic actions may however be positively harmful for carrying out metallurgical processes. According to CONRAD (see *Stahl u. Eisen*, 1909, p. 796) we obtain a purer product when using alternating current for the manufacture of ferro silicon, than when using direct current. For when using continuous current the impurities of the charge are reduced, such as calcium, aluminum and other metals, which then find their way into the final product.

The designers of the electric furnaces for the iron industry today use alternating current exclusively, because they fear the undesirable influences in the charge due to direct current. It may not be out of place to quote the words here of an ardent supporter of electric furnaces for the iron and steel trades. We quote, therefore, from Prof. Borchers and his address in 1905, a translation of which might be called:

"Electrolytic effects were not sought in most reduction and melting tests, whether they endeavored to produce pig iron, or make steel, even though these electrolytic effects are nowhere entirely eliminated. This was particularly so in the arc proc-

esses of earlier periods, where testers positively failed, when endeavoring to produce irons low in carbon. If for instance the iron to be smelted makes one pole of the arc, and carbon blocks the other, then the iron absorbs carbon equally well, whether direct or alternating current be used. We know that an arc between two carbon poles carries carbon vapor across from one pole to the other. For the evaporating point of carbon determines the arc temperature. If one of the poles consists of iron, then the only material remaining for the other pole is carbon, provided direct arc heating is used. In this way the iron will gradually become saturated with carbon even with alternating current. Though we assume that the carbon in the arc wanders only from the anode (positive pole) to the cathode (negative pole), it is evident that the carbon separates itself in its solution in such a way, during a current wave, in going from the carbon pole to the iron, that only a small part of it would return during the current alternation."

We perceive, therefore, that we must guard against the harmful absorption of carbon by suitable means, when using furnaces operating with carbon electrodes, even when working with alternating current.

This is accomplished today by interposing a layer of slag between the arc and the iron, in all furnaces where the arc impinges directly on the metal. This slag is then, to be sure, acted upon in a reducing manner by the arc, yet the iron is protected from any union with carbon.

In accordance with the foregoing, then, we may definitely establish that no electrolytic action takes place in the great majority of furnaces, which operate exclusively with alternating current.

## MOTOR EFFECT

In the construction and operation of electric furnaces we have to take into account the motor effect of the electric current as well as the thermal and chemical effect.

It is just as easy to transform motion into electricity as the reverse, as is very evident from the wide application of the electric motor.

It exceeds the limits of this book to explain the motor phenomenon in detail, still in order to understand and have a correct opinion of the possible and impossible motions of the molten metal in electric furnaces, it appears desirable at least to discuss briefly the reasons for the motion phenomena.

It is well known that an ordinary magnet attracts a piece of iron brought into its vicinity, and that motion is caused by means of this magnetism. It is equally well recognized *that two magnets, like magnetic poles, repel one another; while unlike poles attract one another.*

We also speak of lines of force, which surround the space near a magnet, and it is to these lines of force issuing from a magnet that we attribute the distant magnetic effect. Suppose we have two magnets as Fig. 19 shows with their like poles laid next to each other. If we draw the path of the lines of force as shown we may define the repelling action of like poles, by saying:

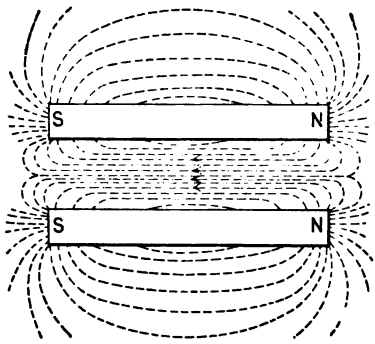



FIG. 19.

*Lines of force having the same direction repel each other; those of opposite direction attract each other.*

We also obtain motion phenomena, therefore, in accordance with this rule, as a result of two magnets acting on each other.

But we will also have these motion phenomena, if a stationary current carrying conductor is brought near an ordinary suspended magnet. In order to do this we may set up an easily movable magnetic needle in its case, and directly above it stretch a wire, which may be connected to a source of electricity. As soon as the current is switched on, the needle will endeavor to set itself at right angles to the wire. The size of the deflection is a direct measure of the current passing through the wire. We find that the deflecting power decreases as the conductor is moved away from the magnet parallel to itself; that the direction of the

needle is reversed when the wire is under instead of above the needle; and that at every position the deflecting power is proportional to the current.

These phenomena prove that a current carrying wire is surrounded by lines of force throughout its whole length, whose density is greater in the immediate vicinity of the wire, which decreases as the distance from it (the wire) increases. Accordingly we may imagine the fields of force of a current carrying wire about as shown by Fig. 20. It is assumed here that the conductor pierces a sheet of paper. On this are drawn the lines of force as they would appear when the current flows. The proof of these lines of force existing concentric to the conductor may easily be had, if a glass plate is used in place of the paper, which is strewn with iron filings. If an electric current is then sent through the wire, which pierces the plate, the iron filings will arrange themselves in direction and density, in accordance with the lines of force. *The direction of the lines of force* may then be established in compliance with a single rule: *If the current carrying conductor is grasped in the right hand so that the outstretched thumb indicates the direction of the current, then the lines of force will encircle the wire so that they would issue from the ends of the remaining fingers.*

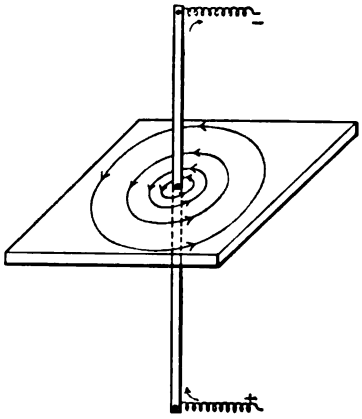


FIG. 20.

If we now return to the first test, in which a movable magnet was brought into the magnetic field of an electric conductor, then in diverting the magnet we have a motion phenomena, pursuant to mechanical power, which appears between electric currents and magnets.

We can now go a step further and replace the second magnet by a conductor. through which current flows. Even then certain

phenomena will be observable, provided one of the conductors carrying current is movable. For until now, we have found that the motion phenomena are the result of magnetic fields which mutually affect each other. As we have also seen that each conductor carrying current has its own magnetic field, then, in accordance with the foregoing, the appearance of mechanical power is unavoidable, between current carrying conductors lying closely together.

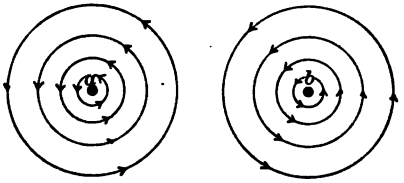


FIG. 21.

Accordingly we may immediately determine the direction of the motion. Suppose we have two conductors both of which carry current going in the same direction, as shown by Fig. 21 at *a* and *b*, here the current would be flowing toward the reader. According to the foregoing rule the direction of the lines of force is quickly determined and is shown by the arrows. We see,

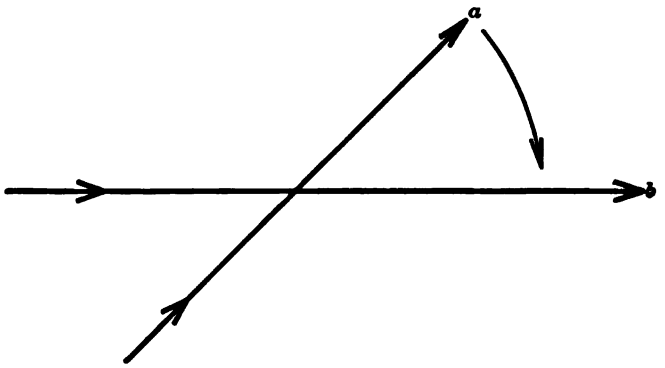



FIG. 22.

therefore, in the space between the two conductors that the direction of the lines of force are opposite to each other. As the lines of force of opposite direction attract each other, we may say relative to the current: "*Currents of like direction attract each other*" and "*currents of opposite direction repel each other.*"

From this it follows that crossed currents and their conductors (as shown by Fig. 22) endeavor to arrange themselves parallel to each other, and in such a way that the current in both flows in the same direction. That is, the movable conductor *a* tries to assume the same direction as the stationary conductor *b*.

The case is also very interesting where one current flows vertically to the other, as shown by Fig. 23. Here the circles or dots represent the points of the arrows, which indicate the direction of the lines of force, while the crosses represent the ends of these arrows.

As lines of force in the same direction repel each other, and those of opposite direction attract, then the movable conductor *a* will endeavor to move in the direction as shown by the arrow.

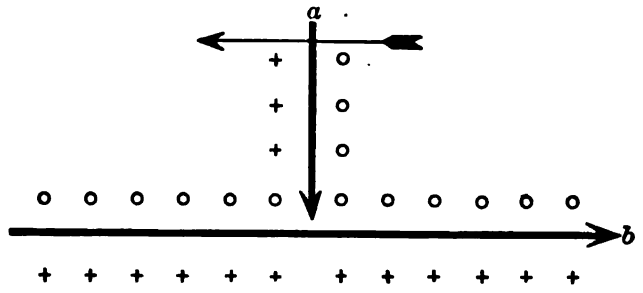



FIG. 23.

In place of the above simple case we may throw some light on the possible motion phenomena in arc furnaces, which may arise due to the electrical conditions which have their electrodes pointed directly against the bath.

We may have the effect of two or more currents acting on each other. In this case one of the conductors, namely the molten metal, may be regarded as being movable, within certain limits. For the molten conductor may be mechanically, comparatively easily influenced, even if only within the limits of the hearth.

The conditions are also very similar with induction furnaces, excepting that in the place of the one solid conductor, we have a

coil of many turns. Figs. 24 and 25 show how the lines of force act: in the former case with the turns wound far apart, and latterly with the turns wound closely together. It follows, therefore, that coils such as these are surrounded by like lines of force as common rod magnets would be, and thereby the laws are known which govern the motion phenomena between active coils and single conductors.

Aside from the above explanations it still seems desirable to mention a very special motion in molten conductors, through which current is passing, but which only arises in certain cases. This is the so-called "pinch effect."

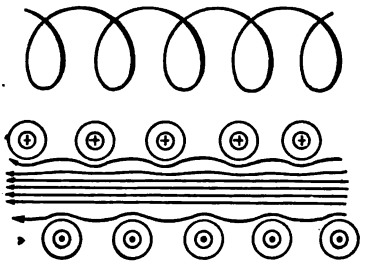


FIG. 24.

According to an address by *CARL HERING* before the Canadian meeting of the "American Electrochemical Society," in May, 1909, this pinch effect occurs when a continuous or alternating current flows through a molten conductor. Then this conductor endeavors to contract itself in the line of its cross-section under the action of electro-magnetic forces. The contracting force is only small, when the current density is low, but grows with increasing current density (amperes per square millimetre or square inch), and can, in extreme cases, become so large, that the cross-section at the contracting point may decrease to zero, thereby interrupting the current. The contraction primarily occurs at such places in the hearth which have already been contracted owing to occasional irregularities when tamping the lining material in place. The fluid column of metal conducting current is therefore interrupted at the weakest place in its cross-section, exactly as a rope breaks at its weakest place. In addition to this, there is a depression where the cross-section diminishes, and on this slanting fluid conductor, particles of slag and the like are apt

FIG. 25.

to follow, which then cause a further increase in the current density, as the conductivity of these impurities is less than that of the molten metal. Furthermore this would be caused at places where the cross-section is already weakened, so that thereby the actions of the pinch effect would be still further increased.

This course of things, as pictured above, does not take place in any deleterious or unpleasant fashion with electric furnaces as they are used for the most part in the iron industry today. As the pinch effect only appears with comparatively high current densities, we find that it does not occur at all in arc furnaces. But it causes various motion phenomena with induction furnaces, as we shall presently explain. Motion phenomena which are entirely desirable and advantageous for the working of metallurgical processes, may be brought about by artificially narrowing the cross-section of the bath to accomplish the required result. These, by their very nature, would in no way endanger the electrical furnace operation.

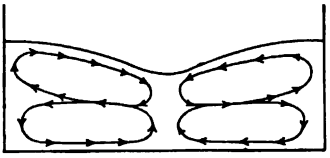


FIG. 26.

An explanation of the appearance of the pinch effect may be had, if we assume that the fluid mass is composed of many parallel connected conductors, which are all leading like directional currents through them. As currents having the same direction attract each other, the foregoing sentence is applicable here, for in a measure it defines the contracting effect.

In electrical furnaces, where the pinch effect causes motion, the liquid seems to be driven along a straight line from the middle and the centre axis toward the ends, so that the fluid mass is lower in the centre than at either end. The weight of the molten metal then causes a flow from the higher lying parts, toward the lower middle section, as shown by Fig. 26. Here the molten conductor is considered to be cut vertically, in the line of the horizontally running current. Without going into further details, it is evident that the motion due to the pinch effect causes an intensive mixing of the charge. This occurs as long as the correct agitation is maintained within the desired

limits, for the motion can only advantageously effect a rapid chemical reaction, which is needed between the iron bath and the slag. Besides this the quality of the steel can only be bettered by the greatest possible uniformity which is brought about by this circulation.

# CHAPTER IV

## POWER FACTOR (COS $\phi$) AND ALTERNATING CURRENT THEORY IN GENERAL

In the previous chapter it was shown that direct current, due to its chemical action, is totally unadapted for electric furnaces as used in the steel industry, and alternating current is therefore used exclusively to operate electro-steel furnaces.

The difference between direct current and alternating current is that in the former the current is always flowing in the same

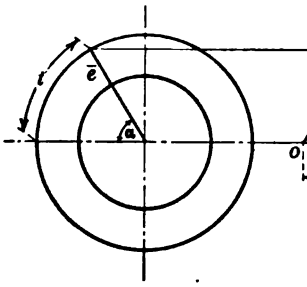



FIG. 27.

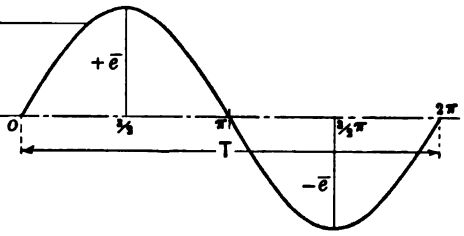



FIG. 27a.

direction, whereas in the latter it changes its direction continually.

The required time for one directional change is called the period and is designated by $T$. Fig. 27a shows a complete wave or cycle. In this figure one cycle, therefore, takes the time, $T$, which is necessary for the current to swing through a complete wave. Hence, one complete cycle goes from $O$ through to the positive maximum, and from zero to the negative maximum and back to the zero point.

For all practical purposes we can assume that the usual alternating current generator gives a sine wave for its electromotive force. This being the case, it only remains to show how

a sine curve is constructed, and to draw another diagram next to Fig. 27*a* showing these relations in alternating current circuits.

If (as in Fig. 27) we let the radius or radius vector equal the maximum voltage reached in this sine curve, and designate this maximum value by $\bar{e}$, the various instantaneous values of the sine curve by $e'$, then:

$$e' = \bar{e} \sin a$$

*i.e.*, for every angle $a$, the ordinates of the sine curve give the corresponding instantaneous potential values as indicated by Fig. 27. In the above equation in place of the angle, however, we can substitute for it the value of the angular velocity and obtain:

$$a = m t$$

(similar to the equation, distance = speed × time), and as the angular velocity $w = \frac{d a}{d t}$ hence

$$e' = e \sin m t$$

where $t$ is the time taken by the radius vector until it has passed through the angle $a$ after leaving the zero or starting point. The whole time corresponding to one cycle is $T$ and the corresponding angle is $2\pi$, and by substituting these values in the previous formula, since ($a = 2\pi$ and $t = T$)

$$2\pi = m T \text{ from which it follows that} -$$

$$m = \frac{2\pi}{T}.$$

It is customary to speak of cycles per second or frequency, and as the time of one cycle is equal to $T$, the frequency $v$ is

$$v = \frac{1}{t}.$$

If we substitute this value in the formula containing $m$, we get $m = 2\pi v$.

We speak of an alternating current of, say 25 cycles, when this current makes 25 waves each second.

The more or less frequently varying direction and strength of the current depending upon the cycles per second, or frequency,

has a particular bearing on the functions of alternating current circuits. In order to understand these, the so-called *induction* will next be briefly described. This seems necessary because a clear conception of the induction phenomena is important, in order to understand the induction furnaces which will later be discussed in detail.

We obtain an inductive action, for instance, when an electric conductor is moved through a magnetic field so that magnetic lines of force are cut. If we connect the ends of this conductor with a measuring instrument we obtain a deflection, showing the presence of an electric current produced by induction. This current is called induced.

We therefore say, " *If a conductor is moved in a magnetic field so as to cut magnetic lines of force, an electro-motive force is produced, which will cause a current to flow provided that the conductor has its ends closed so as to form an electric circuit. The electro-motive force and also the current become larger, as more magnetic lines of force are cut in a given time.*"

It is evident that it makes no difference in which way the magnetic field is produced, because it is only necessary for the conductor to cut lines of force. It is, therefore, immaterial whether the conductor is moved through the field of a permanent magnet or through the field of an electro-magnet. It is even sufficient to move it near a wire through which a current is flowing, because this wire is surrounded by lines of force.

Until now we have assumed that we have moved the conductor in which a current is induced. Instead of that we can move the magnet and hold the conductor; still, as in that case, an electro-motive force is also generated, due to lines of force being cut. We may finally place two conductors side by side, and if we pass a current through one of them, it will generate a magnetic field, the lines of force of which will cut the second conductor. If the current is interrupted, the lines of force disappear, only to reappear instantly upon the current being again made. We therefore have a field of constantly changing lines of force and a conductor located in this field. Hence an e.m.f. is induced in the second conductor, exactly as when a magnet

approaches a conductor from an infinite distance and then recedes again to an infinite distance.

The alternating current changes its strength continually, and, as we have seen, it increases twice during each period or cycle from zero to a maximum and consequently decreases from that point again to zero. As a result of this, a conductor carrying an alternating current is surrounded by an alternating magnetic field, which induces e.m.f., or currents, in all conductors within its field.

The current-carrying conductor itself thus lies in an alternating field and, from what has been said, it is evident that an e.m.f. will be induced in this conductor by its own field. This action is called *self-induction*, and the current generated thereby is called the self-induced current.

This self-induced current always flows in the opposite direction to the current which produces it. If the primary current, for instance, flows to the right, the induced current will flow in the opposite direction, or to the left, in the same conductor. The self-induced current for this reason does not exist, as the effect is to weaken the primary current. If voltage is applied to a coil, therefore, the current does not immediately reach its maximum value, but does so only after a certain time-interval has elapsed. The highest value is reached after the lines of force are no longer on the increase. We therefore say the current lags behind the voltage.

It should be remembered that we obtain the instantaneous values of the voltage as the projections of a rotating radius vector. Therefore, we can likewise get the instantaneous values of the current as projections of a radius vector of a different value. We then obtain the lag of the current behind the voltage, and draw this lag out in the form of a definite angle. This angle is then the measure of the lag. Time difference between current and voltage we call phase displacement,—and the angle which the radii vector of the current and voltage make with each other is called the phase angle. The letter $\phi$ has been commonly chosen to designate this angle.

We have for instance the vector diagram Fig. 28, which

pictures the relations as they might be in an alternating current circuit. We have only to imagine the radii vector as rotating about $O$ as a centre, to obtain at any time the corresponding values of the current and voltage by drawing the vertical projections of their respective radii vectors.

Sometimes this vector diagram is drawn even more simply,—see Fig. 29.

On what conditions now does this phase displacement depend?

We have already seen that this phase displacement is a result of the self-induction. Therefore, the greater the current

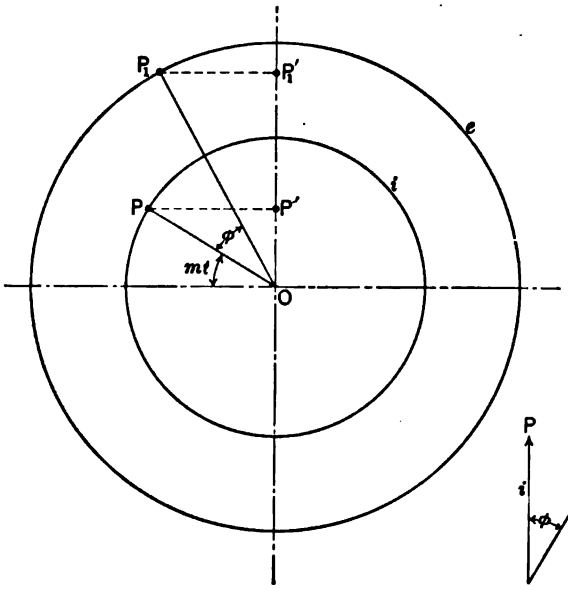



FIG. 28.

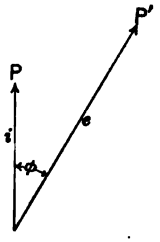



FIG. 29.

and the faster the changes, the greater is the change in the corresponding magnetic fields, in a given time. The frequency therefore, has a large influence on the phase displacement.

Besides this, the self-induction is also dependent on the type of conductor used and its position relative to other conductors. The factor which designates these conditions is called the "coefficient of self-induction." The mathematical symbol for this is "$L$."

We therefore say:

*The electro-motive force of self-induction is proportional to the coefficient of self-induction, and to the rate of change of current per second, or the frequency.*

If we compare the relations in an alternating current circuit with those in a direct current circuit, we see, in the latter case, that it takes a definite voltage to force a current $i$, through the resistance $r$, and, according to Ohm's Law, we have

$$e = i \times r$$

If it is desired to send an equal alternating current, $i$, through a coil, it also takes a certain voltage,

$$e_r = i \times r,$$

to overcome the resistance.

We have to take into account, though, that with alternating current an electro-motive force due to self-induction is generated, which is always in the opposite direction to the impressed electro-motive force.

In order, therefore, to obtain the desired current $i$, we need not only the voltage, $e_r = i\,r$, but also an additional pressure $e_L$ to overcome the electro-motive force of self-induction. Hence, the total voltage necessary for an alternating current is,

$$e = e_r + e_L.$$

The alternating current voltage $e$ is composed of two different pressure waves. These waves are displaced by an angle of 90° or ¼ of a period, which can easily be shown by a short mathematical demonstration.

The above sentence in italics regarding self-induction, is mathematically expressed as follows:

$$e_L = L \frac{d\,i}{d\,t}.$$

Furthermore, we know that for a sine wave, the formula for an alternating current at any instant is:

$$i' = \bar{\imath} \sin m\,t,$$

exactly as the sine wave for the voltage gave

$$e' = \bar{e} \sin m\,t.$$

If we substitute another value for $i$ in the equation

$$e_L = L\frac{di}{dt} \text{ we obtain}$$

$$\frac{di}{dt} = \frac{d(\bar{\imath}\sin mt)}{dt} = m\bar{\imath}\cos mt$$

$$e'_L = (m \times \bar{\imath} \times L)\cos mt.$$

We have $e_r = ir$ or the instantaneous value

$$e'_r = (\bar{\imath}r)\sin mt.$$

The total voltage is, therefore,

$$e' = e'_r + e'_L = (\bar{\imath}r)\sin mt + (\bar{\imath}mL)\cos mt$$

and as $\cos mt = \sin(mt + 90°)$ it is evident that the voltage necessary to overcome the counter electro-motive force of self-induction is 90° ahead of the e.m.f. necessary to overcome the ohmic resistance.

From this it follows that these two e.m.f.'s are not to be added arithmetically but geometrically. If we draw this as shown in Fig. 30, we have:

$OA$ = maximum value of the current = $i$

$OB = e_r = \bar{\imath} \times r$

$OC = \bar{e}_L = \bar{\imath}mL$

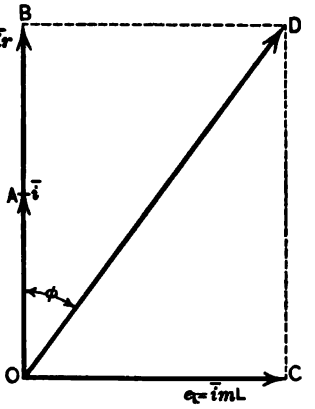



FIG. 30.

The resultant of the two e.m.f.'s is graphically shown as $OD$, and from it we obtain the total voltage

$$e = e_r + e_L.$$

From the figure then we have:

$$e = \sqrt{e_r^2 + e_L^2}$$

$$= \sqrt{\bar{\imath}^2 r^2 + \bar{\imath}^2 m^2 L^2}$$

$$= i\sqrt{r^2 + m^2 L^2}$$

It also follows that $\tan\phi = \dfrac{mL}{r}$ when $\phi$ is the phase angle

between the current and the voltage.

It is worthy of mention that from the equation

$$e = i\sqrt{r^2 + m^2 L^2}$$

it seems as though the self-induction apparently increases the resistance. Hence, the expression

$$\sqrt{r^2 + m^2 L^2}$$

is also called the "apparent resistance" of an alternating current circuit. In order that there shall be no mistake regarding the values which are indicated by measuring instruments in alternating currents, it is well to emphasize here, that so far we have only mentioned the instantaneous and maximum values. As a matter of fact, neither of these values is indicated by the usual alternating current instruments. These values have only been used to more clearly state the relation in a.c. and to make them easier to understand. The instantaneous and maximum values are therefore only of theoretical interest, whereas the a.c. instruments indicate a so-called "*effective value.*" This is obtained from the previous formulas and figures by dividing the maximum values by $\sqrt{2}$. Hence, the effective value of the voltage is $e = \frac{\bar{e}}{\sqrt{2}}$ and the effective value of the current is

$$i = \frac{\bar{i}}{\sqrt{2}}$$

We can therefore regard the diagrammatic figures as representing the effective values, as these only differ from the maximum values by a constant factor.

If we now return to the phase displacement between the current and voltage, we find the question becomes of the greatest interest.

What influence has the phase displacement on the power computation?

It was shown in Chapter II. that the power in watts is equal to the product of the current and voltage, that is $p = e \times i$. Unless the so-called power factor, which will be later explained, is unity, this last equation is only applicable to direct current.

Whereas for alternating current the formula becomes,

$$p = e\,i\cos\phi.$$

In this equation $e$ is the effective voltage, $i$ the effective current and $\cos\phi$ the power factor.

In alternating current circuits we call the product $e \times i$ the apparent power. It is measured in volt-amperes or kilo-volt-amperes = 1000 volt-amperes. The product $e\,i\cos\phi$ designates the real or effective power and is measured in watts or kilowatts. To verify the equation for the true power really goes beyond the limits of this book. For those, therefore, who are interested in this paragraph, it is added in an abbreviated manner.

The equation for the instantaneous energy is

$$p' = e' \times i'.$$

The work done in ½ a period during the time $\frac{T}{2}$ is then

$$A = \int_o^{\frac{T}{2}} e'\,i'\,dt$$

and from this we obtain the mean value of the energy.

$$p = \frac{1}{\frac{T}{2}}\int_o^{\frac{T}{2}} e'\,i'\,dt = \frac{2}{T}\int_o^{\frac{T}{2}} e'\,i'\,dt$$

by substituting the values $i' = \bar{\imath}\sin m\,t$ and

$$e' = \bar{e}\sin(m\,t + \phi)$$

and by completing the integration, we obtain,

$$p = \frac{\bar{e}\,\bar{\imath}}{2}\cos\phi \text{ and as}$$

$$\frac{\bar{e}}{\sqrt{2}} = e \text{ and } \frac{\bar{\imath}}{\sqrt{2}} = i \text{ we get } p = e\,i\cos\phi.$$

From this it follows that, providing the voltage and power remain unchanged, the current decreases with an increasing power factor. As the current strength determines the cross-section of the electrical conductor, it naturally interests us to keep the current down, *i.e.*, we strive to obtain the highest possible power factor.

From the above power equation, it follows that, when $\cos\phi = 1$,

$p = e\,i$ and the angle $\phi = 0°$. The other limit is when $\cos\phi = 0$ or the angle $\phi = 90°$, then the power, $p = 0$. A low power factor, therefore, corresponds with a large phase displacement. The meaning of the above may best be enlarged upon by an example:

Suppose the electrical circuit contains a coefficient of self-induction $L = .002$ henry
a resistance $r = .0125$ ohm
a frequency $\nu = 50$ and therefore $m = 2\,\pi\,\nu = 314$
voltage $e = 150$ volts.

Then:

$$\tan\phi = \frac{m\,L}{r} = \frac{314 \times .002}{.0125} = 50.24.$$

The angle $\phi$ corresponding to this value is then 88° 50′ or nearly 90°. Hence $\cos\phi$ is nearly zero.

The relations are graphically shown in Fig. 31. This shows

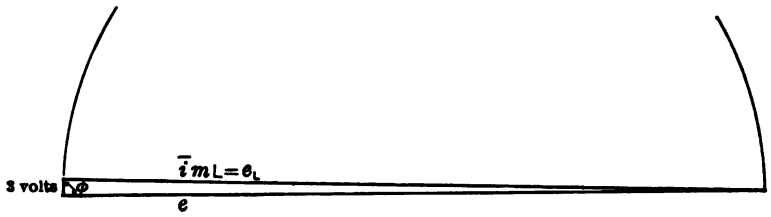



FIG. 31.

that $e$ and $e_L$ almost coincide, so that $e_L$ practically equal $e$.

The current is then

$$i = \frac{e}{m\,L} = \frac{150}{.628} = 240 \text{ amperes.}$$

Consequently $i\,r = 240 \times .0125 = 3$ volts $= e\cos\phi$
and

$$i \times e\cos\phi = 3 \times 240 = 720 \text{ watts.}$$

With the same current but with $\cos\phi = 1$, we would have obtained instead of the above, the power $p = 240 \times 150 \times 1 = 36000$ watts.

This example shows us plainly how impossible it is to judge the power in an alternating current circuit by merely reading

the ammeter and the voltmeter, as these two instruments do not in any way indicate what the power factor is. We therefore employ a special instrument to measure the power, a so-called wattmeter, which indicates the watts or kilowatts, directly, where

$$1 \text{ kilowatt} = 1 \text{ kw} = 1000 \text{ watts.}$$

As the example showed that the voltage necessary to overcome the e.m.f. of self-induction (*i.e.*, the vector $e_L$) is without any influence on the actual power—in other words, it delivers no power which can be measured in watts—we therefore call this vector the wattless component, and the vector $e_r = i \times r$ is called the watt component of the voltage.

Up to the present we have divided the voltage into two component parts. The one being the watt component $e_r = i\,r$ which coincides with the direction of the current, the second being the wattless component $e_L = i\,m\,L$ which is in quadrature with the former.

The power $p = e\,i \cos\phi = i\,(e \cos\phi)$ where $e \cos\phi = e_r$; that is, the power is obtained by multiplying the two unidirectional vectors or forces ($i$ and $e_r$). (See Fig. 30.)

Instead of separating the voltage into two components, we could have also separated the current into two forces at right angles to each other. This separation can be done in such a way that one force falls in the direction of the terminal voltage, and being multiplied with this, it gives the resultant power, while the other force is perpendicular to the first one.

The equation for the power,

$$p = e\,i \cos\phi \text{ can be written}$$

as

$$p = e\,(i \cos\phi) = e\,i_r$$

where $i_r$ is the watt component of the current and equals $i \cos\phi$.

Taking then the values of the example as chosen, we obtain Fig. 32. The directional precedence is given by the curved arrow. Here the total current, $i$, is shown as lagging behind the voltage by the angle $\phi$, similarly to the previous example. As the angle $\phi$ is approximately 90°, then $i$ and $i_m$ almost coincide and the wattless component of the current is

$$i = i_m = 240 \text{ amperes}$$

whereas the watt component of the current $i_r$ approximates zero.

It is therefore apparent that the total current $i_m$ is only present in order to generate the e.m.f. of self-induction. In other words:

It is the wattless component of the current which generates the lines of force. That is why this wattless current is also called the *magnetizing current*, and this is why it is designated by $i_m$ in the accompanying figure.

It follows, therefore, from all which has been said of the power factor that: When figuring the size of electrical conductors, the apparent power should always be the determining factor, *i.e.*, the product $e \times i$ or current $\times$ voltage, in other words, the kilo-volt amperes. On the other hand, the power of the prime

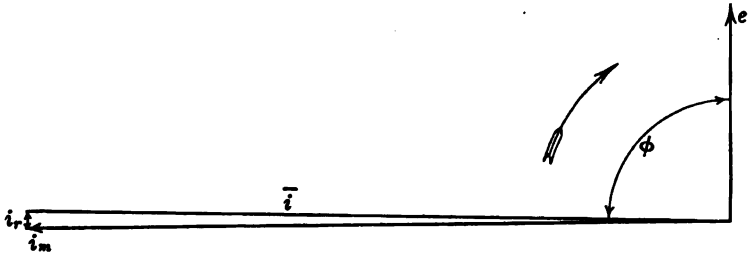



FIG. 32.

mover only takes into account the actual power, that is the product $e\,i \cos \phi$ or the actual kilowatts. *In other words, a poor or low power factor means expensive lines and electrical machinery, whereas it has no influence whatever on the prime mover.*

It is apparent, therefore, that it is in the interests of an inexpensive installation to have an acceptable power factor. It is to be noted, however, that in the ordinary power houses, the power factor varies between .6 and .8, depending on the sizes of the motors used and at what load these are operating. These values are, therefore, a guide indicating whether or not we have a good power factor.

Quite independent of the current lag, we may have induction phenomena which will call forth other and more disagreeable actions than those shown, and as it is the object in designing and

operating electric furnaces to avoid these troubles, we will mention them briefly.

We have seen that an alternating current in a conductor will generate another alternating current in any conductor if the second conductor only lies in the magnetic field of the first conductor.

We therefore obtain currents in all conductors which lie in the magnetic field of another conductor, and these currents may cause considerable power losses under certain conditions. It would lead us too far if we were to occupy ourselves deeply with these phenomena. On that account only those possibilities will be mentioned which lead to these power losses in electric furnaces, and the remedies which help to overcome these losses.

In the first place there are the induced currents themselves, which may engender considerable losses. As these induced currents are generated in every conductor which is parallel to the main current, they may cause great losses when the conductor carrying the induced current is short-circuited. It is therefore necessary to avoid all designs in which, for example, an iron beam would follow a main conductor, so that it would then be short-circuited on itself. This condition is to be considered only when very heavy currents are present as is altogether the case with electric furnaces. But even here these actions may be avoided by carrying the incoming and outgoing conductors close together. In this way the magnetic fields—for instance those made by the two conductors of a single phase circuit—are then neutralizing each other, so that we have no action on parallel lying and closed iron parts. There are, however, currents induced in every metal part which is near an alternating current carrying conductor. These metallic parts provide splendid conductors for the current through which the current may be short-circuited, so that under certain circumstances a metallic piece of that kind may reach really unlooked-for temperatures. We call these *eddy* or *Foucault currents*. They are particularly prevalent when the metal in question is magnetic, that is, a good conductor for the magnetic lines of force. There would be considerable losses, for instance, in the cooling chambers used in electrode furnaces, to cool the electrodes, if these were made of cast iron

or cast steel, as both of these materials carry the magnetic flux better than air. We are, therefore, obliged to make these cooling chambers out of copper or red brass, as both of these materials are non-magnetic.

Another method used to lessen these eddy current losses, is to greatly subdivide the metallic parts in which these eddy currents might appear. Transformer and dynamo armature cores are examples. These cores are built up of sheets as thin as .5 and sometimes only. 3 mm. (.02 to .012 inch).

Finally we might also have the case where a good magnetic conductor, one of low magnetic reluctance, entirely surrounds an electric conductor. If the magnetic conductor should have a considerable cross-section, then certain power losses arise, due to the constant demagnetizing influence of the alternating current. This loss is known as the *hysteresis* loss. For this reason, therefore, we also avoid surrounding electrical conductors with good magnetic conductors in electric furnace construction.

It seems well to mention that besides *single phase alternating current, polyphase* (*2 or 3 phase*) alternating current is also used to operate electric furnaces. In order to understand these power circuits, we will add the following:

Three phase current is visually distinguishable by having three lines which conduct the current from the source of supply to the apparatus using it. Whereas with single phase current there are only two lines, one line to lead the current to the destination and one return wire.

As the name three phase implies, we use three conductors and handle three currents in this power transmission. The vector diagram shows us this the plainest, *i.e.*, the relations between these currents and what the relations are between the different values occurring in three phase power transmission.

Fig. 33 shows us three vectors which are separated 120° from each other. These vectors indicate the direction of the current as they are actually generated in 3-phase machines and actually consumed in 3-phase apparatus. If we add these currents geometrically, as shown in the figure, we observe that the geomet-

rical resultant of two current forces always equals the third current. This explains why only three lines are necessary to

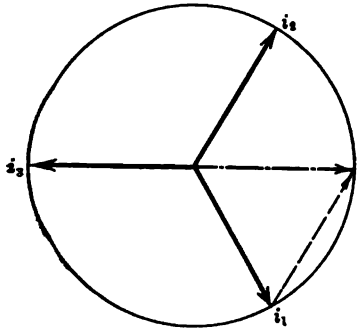



FIG. 33.

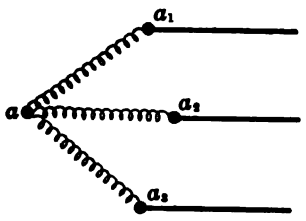



FIG. 34a.

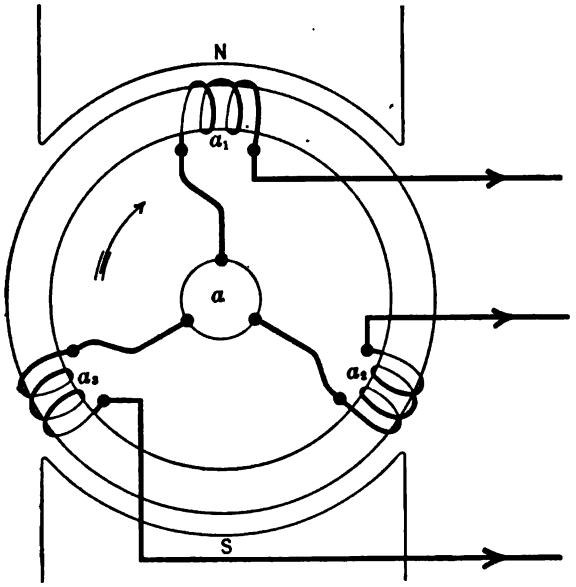



FIG. 34.

conduct a 3-phase current, of which the third conductor may be looked upon as a return wire for the other two. This presupposes of course that the current in each direction or phase is of the same value.

The coils of the generator or those of the power consuming apparatus which are built for 3-phase current, may be connected

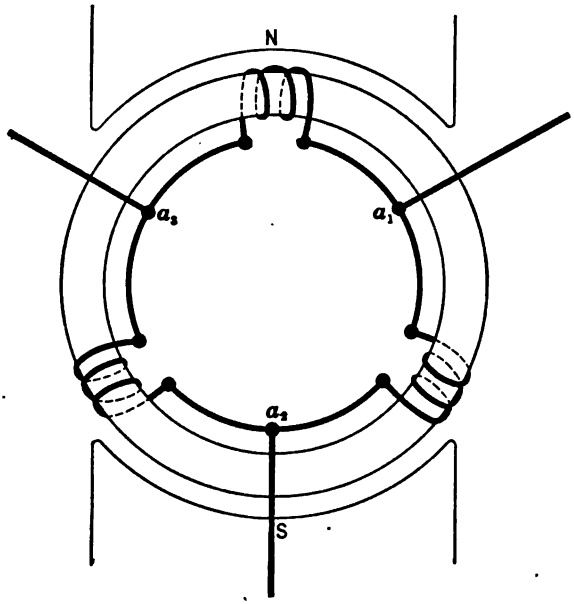



FIG. 35.

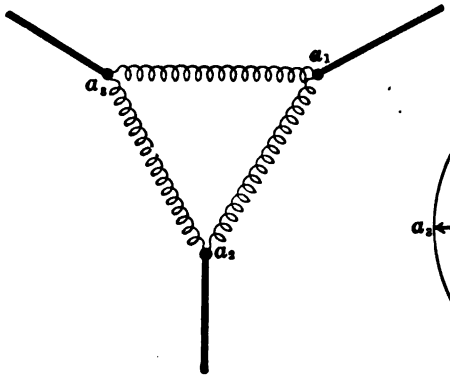



FIG. 35*a*.

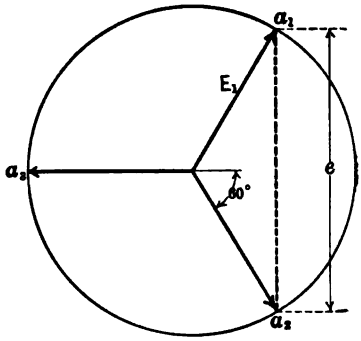



FIG. 36.

in two different ways with each other. Fig. 34 shows the so-called *Star* or Y connection, in which the ends of the coils of the generating or receiving apparatus are connected together at the

*neutral* point $A$, whereas Fig. 35 shows the so-called *Delta* connection in which the single coils are connected in series, and the connecting points of the coils are led off to the power mains.

With the Star or Y connection we may have either the voltage of one phase or the resultant voltage of two of the phases. The first is the potential between the neutral point $A$, Fig. 34, and the end of one generator coil, as shown by the connections $A\,a = A\,a_2 = A\,a_3 = E$. The other voltage is the resultant of two of these coils and is across the points $a\ a_2$, $a_2\ a_3$, $a_3\ a$, and this resultant voltage is designated by $e$. If in these Star connections the phase voltages should be different, there would however be no difference between the currents flowing in the generator coils and on the line. If $I$ = generator phase current, and $i$ = line current, then $I = i$, as is evident by consulting Fig. 34.

If we, however, view Fig. 35, we instantly perceive that the phase voltage and line voltage are equal to each other or $E = e$. On the other hand we have different values for the current per phase and the line current. With 3-phase currents for electric furnaces the Y connection is mostly used. What is the relation between these two voltages?

If we have the phase voltage $E$, we may obtain the resultant voltage by taking the geometric difference between any 2 phase voltages. If we refer to Fig. 36 we see that, $\sin 60° = \frac{e}{2} E$ and therefore the resultant voltage

$$e = 2\,E \sin 60°$$
$$= \sqrt{3}\,E = 1.73\,E.$$

In the same way it may be shown for $\Delta$ connection that

$$i = \sqrt{3}\,I$$

These relations must be known in order to clearly understand the power in 3-phase circuits. We can imagine the 3-phase power being equal to the sum of power of the 3 single phases.

We then obtain,

$$p = E_1 I_1 \cos\phi + E_2 I_2 \cos\phi + E_3 I_3 \cos\phi$$

and as we assume that the separate phases are balanced or equally

loaded we may write that

$$p = 3\,E\,I\cos\phi.$$

We saw for the Y connection that $e = \sqrt{3}\,E$ and $i = I$. If we substitute these values in the power equation, we have

$$p = 3\,\frac{e}{\sqrt{3}}.i\cos\phi = \sqrt{3}e\,i\cos\phi$$

*i.e.*, we obtain the power in a 3-phase circuit by multiplying the current by the voltage by the power factor and the product by $\sqrt{3}$.

Finally, it may be said that we have wattmeters which measure the total power, $p = \sqrt{3}\,e\,i\cos\phi$ in 3 phase circuits. It is therefore an easy matter to determine the power factor in a 3-phase circuit, provided other instruments give the values of the current and voltage of the 3 balanced phases.

We therefore have

$$\cos\phi = \frac{p}{3\,e\,i.}$$

In the above $p$ = total power in either a Y or $\Delta$ connection circuit as measured by a wattmeter. $i$ = the current in each line, sometimes only measured by one ammeter, and $e$ = voltage as measured by the usual a.c. voltmeter.

# CHAPTER V

## GENERAL CONDITIONS FOR THE OPERATION OF ELECTRIC FURNACES

BEFORE we deal with the furnace designs now largely used for steel making, it may be well to discuss a few general questions. An understanding of these is of great importance in order that we may correctly judge an electric furnace.

First and foremost the question arises:

Why has the steel industry in general an interest in electric furnaces, and what advantages does the electric furnace offer compared to the existing metallurgical apparatus?

It is obvious that the advantages will have to be of some moment, if the iron masters are to discard or supplement their hitherto satisfactory methods of procedure.

It behooves us then to consider first the proved and peculiar heating effects derived entirely from electricity. We find the following characteristics:

1. The use of electricity as a heating agent makes an extraordinary and quick heat possible, which same is impossible with any system of gas heating. Here it may be noted, that before the introduction of the electric furnace into the steel industry, it was only possible to make refractories stand temperatures of 2000° C., whereas we may now reach any temperature up to 3500° C. in the electric furnace.

2. With the aid of electrical control the heat can be regulated most accurately, so that the charge can be brought to any desired temperature and kept there, according to the demands of the process in question.

3. Electricity offers us the cleanest heating agent imaginable; so that we are enabled to avoid all deleterious influence which other heating agents have; for electric furnaces allow us to operate in any atmosphere, and this prevents reactions taking place

which may be caused by atmospheric elements, gases, or the products of combustion.

4. The characteristics noted, in sections 1 and 3, allow the steel bath to be refined to any high degree. Sulphur particularly may be entirely eliminated, so that a high class finished product may be made from impure and cheap raw material.

5. The electric furnace allows us to make crucible quality steel in large quantities (as mentioned in section 4), made from cheap raw material, and yet, at the same time, it turns out a completely homogeneous product. This product has hitherto been possible only in the crucible furnace, where many separate crucibles are used charged with the purest and most expensive of raw materials.

6. In many cases the product of electric furnaces shows crucible quality characteristics, even though the cheapest metal had been charged. This high quality cannot be achieved in any other type of furnace. The reason for this being that the heating agent does not in any way influence the charge and therefore the steel may stay in the electric furnace as long as deemed best, and held at any desirable temperature, meanwhile allowing the gases to escape.

As these are the general principles which make the electric furnace valuable to the iron industry, it seems advisable to state the requirements which an ideal electric furnace would demand in order that the above advantages may be best attained. Particularly as the number of different furnace designs are numerous.

Surely everybody who is confronted with the question of installing an electric furnace, will see first that the installations shall cost the least amount of money, and second that the type used combines the greatest simplicity with the greatest safety during operation.

The requirements, therefore, should be as follows:

1. The ability to use any prevailing alternating current at any voltage and frequency.
2. The avoidance of any sudden changes in the load.
3. Ease of regulating the incoming current.
4. High electrical efficiency.

To which are added the following:

5. A furnace of the tilting variety.

6. Easily surveyed and accessible hearth.

7. The electrical heating or any of its necessary auxiliaries must in no way influence the chemical composition of the steel or the slag.

8. The ability to reach any desired uniform temperature in all parts of the bath, and at the same time avoiding any local under- or over-heating.

9. The furnace should be as versatile in its application as possible. These requirements further stipulate the following:

10. Equally advantageous, rapid, and inexpensive methods of removing all impurities contained in the charge, notably sulphur and phosphorus, and furthermore:

11. The possibility of completely and easily removing any slag in the furnace, and of being quickly and easily able to renew it.

12. Complete uniformity of the material in all parts of the molten metal and consequently a sufficient circulation in the bath.

13. Avoidance of too much agitation in the bath, and therefore providing an advantageous standing of the metal.

14. The possibility of providing various furnace sizes, which would have to fit prevailing conditions.

15. The highest possible thermal efficiency with all furnace sizes.

16. The avoidance of all water cooling.

17. The least possible refractory and initial cost and low-operating cost.

It may be again remarked that the above requirements are those which would be expected of an *ideal* furnace. The furnaces discussed in the following chapters are those in practical use and therefore only partly fulfill the above requirements, some more and some less, so that the exactions made of an ideal furnace only serve as a normal estimate, with which the following various designs are compared.

First of all, though, it seems necessary to dwell more intimately upon the importance of several points.

1. Of the furnace operation we required the use of *any prevailing current.*

If this requirement were fulfilled it would enable any electric furnace to be connected to an existing central station, no matter if this were a city electric plant or the works' own isolated station. If the electrical power was sufficient in either case, only the connection to the furnace installation and the latter itself would be necessary, so that the expense of a special generator, which would only be ordered for the furnace itself, would be saved.

If, on the other hand, the case should present itself where the available power of an existing isolated plant was entirely in demand for other purposes, then in this case it would also be advantageous if any available current could be used for the electric furnace, so that the generator installation furnished for the electric furnace could at the same time and in any event be used as a reserve for the remaining generators; or the generators would act as a mutual reserve, as well for the main generator installation as for furnace generators, which would then insure the best service conditions.

If the consumer of electric current does not have to take into consideration the conditions existing in a distant central station when connecting to its lines, then such a connection also offers important advantages as it enables the existing central station current to be used. Furthermore the furnace installation in this case can easily be erected in a comparatively small place, besides saving the attendance for one's own power plant, or that required for a rotary transformer. This is entirely independent of the fact that *small* works are hardly able to generate power as cheaply as it can be sold by large central stations, excepting when high pressure internal combustion oil-engines are used.

Accordingly, it would be desirable, of course, if direct or continuous current could be used for operating electric furnaces, in case a steel mill only possessed a direct current power plant. We, however, saw in the third chapter that on account of the chemical action of direct current, this does not appear suitable

for operating electric furnaces, and as direct current can only be changed from a higher to a lower voltage, such as is used for arc furnaces, by means of expensive rotary converters, consisting of driving-motor and generator, and if the continuous current were to be used directly from a low voltage plant, the cost of the connecting wires and cables would be extraordinarily expensive, as the distances are usually considerable; therefore, direct current is practically never used today for any electric furnaces in the iron industry. If, in spite of this, we see the assertion made here and there in advertising mediums, that a furnace may also be operated with direct current, then these assertions are to be approached with the greatest care, for when these are accurately tested, it will always be found that such allegations are misleading.

It can accordingly be established that direct current does not come into play at all for operating electric furnaces. These latter may, however, be adjusted to any conditions which are offered by the modern *alternating current station.*

It is well known that at present alternating current stations are built for three phase current, because the electrical conditions are especially favorable. When an electric furnace therefore is to be connected to an existing power plant, we shall no doubt, in the majority of cases, find that it is to be connected to a three phase plant. In this case a three phase furnace shall have a particular advantage which exactly fits into the conditions offered by an existing electric station. A two phase furnace has the same advantage as a three phase furnace, even though the former is to be connected to a three phase circuit, as three phase current may be changed to two phase by means of stationary transformers having the Scott connection. These transformers are necessary in such cases to regulate the power fed to the furnace, *i.e.*, these regulating and phase changing transformers would serve the double purpose of simultaneously changing three to two phase current or *vice versa*, and regulate the current besides. Whereas a single phase furnace under these conditions would necessitate the installation of a rotary transformer, consisting of a three phase motor and a single phase generator,

which would considerably increase both the initial and the current costs. But even though it would be necessary to install a new alternator to deliver current to the furnace, the three phase (or two phase) furnace has certain advantages. In this case it would be of considerable importance to obtain the least expensive electric plant consistent with economic operation. And it may be of determining importance here as a polyphase alternator costs about 25 to 33 per cent. less than a corresponding single phase alternator.

If, on the other hand, single phase current only should be available, then the polyphase furnace would, of course, be more expensive, as the single phase current would then have to be changed to polyphase current by means of a rotary transformer. It appears, therefore, that the utilization of any existing single phase current would be of particular advantage.

It seems that being able to use any voltage is of lesser importance. For as our requirements have limited us to the use of alternating currents, there no longer remains any noteworthy difficulty in changing or transforming a high central station voltage to a lower furnace voltage. For this change can be made very simply, and almost without loss, by means of stationary transformers, which only entail a comparatively small expense, and almost possess an unlimited life.

Contrary to the foregoing, we find that it is of great importance to be able to use any existing frequency for the electric furnace. Unfortunately, this requirement is not yet completely fulfilled, practically, by any of the well-known furnace designs. Among others, the main reason is to be found in the power factor or $\cos \phi$ falling as the frequency rises. (See Chap. 4.)

It can, therefore, only be established, (taking into consideration that only the practically attainable can be asked,) that an electric furnace should be operated with normal frequencies, meaning thereby 15, 25, 50 and 60 cycles.

In order, however, to point out early, of what importance the periodicity of an alternator is regarding the cost, it may be mentioned for instance that the costs of a single phase alternator of 25 cycles and a similar one of equal capacity, but of only five

cycles, will bear the ratio of 1 : 2. These figures may perhaps best show, characteristically, the influence of abnormally low frequencies.

We now come to the second requirement, *viz.*: *the avoidance of all sudden and untoward changes in the load.*

That such load changes and principally current fluctuations are of the greatest disadvantage to every electrical power plant, needs no explanation. It may only be remarked here that no city lighting and power plant would allow an electric furnace on its lines, which operated with heavy power fluctuations, without first interposing a rotary transformer with suitably heavy fly-wheels or other appurtenances which would be able to absorb these fluctuations and thus keep them away from the central station. This same requirement would also have to be met with in every other isolated plant, if any value is placed on its economical operation.

With interposed rotary transformers, therefore, the power fluctuations would increase the initial cost. This also holds, provided the furnace is connected to a special generator. For it is evident that the generator must stand the greatest current fluctuations without injury, *i.e.*, the generator must be built for much higher currents than if there were no irregular power surges. In other words, a generator required to operate a furnace, having current fluctuations, could operate a much larger furnace which was free from such fluctuations. To this must be added the fact that the generator's prime mover would run under much more unfavorable conditions, and with a much poorer efficiency, if the current surges are to be overcome, than if it only had to deliver the power uniformly or at a gradually changing rate. The power delivered to an electric furnace, having power fluctuations, is similar to that taken by an electrically driven rolling mill or by an electric railway.

In order to give an arithmetical example, it may be said that normally turbo-generators have a steam consumption of 7.5 kg. per kw.-hr. (16.5 lbs. per kw.-hr.), whereas turbo-generators for railway service, with their required overload capacity, often have a steam consumption of 8.25 (18.15) and more up to 10 kg. per

kw.-hr. (22 lbs.). These figures about give a correct idea of the advantage which an electric furnace has whose operating force is free from fluctuations. This is quite apart from having a less expensive power plant which a smooth running furnace has. Furthermore, a power plant subject to having power fluctuations, is naturally liable to much greater wear than is occasioned by uniformly loaded machines.

To the third point, *viz.*: the ease of regulating the electric furnace so as to give higher or lower temperatures, nothing more can be added. This is fulfilled as the furnace voltage can be easily changed, by suitable electrical apparatus, so that this requirement is fulfilled by all furnaces in the same way.

Likewise the fourth point leaves nothing to be said regarding the requirement for a furnace with the highest possible efficiency. For, it is self-evident that a poor efficiency would entail a greater power absorption for the same work, and thereby the operating costs might be considerably increased.

The remaining requirements refer mainly to metallurgical facts, which are discussed in detail in the second part of this book. That is why they are only given here just sufficiently to enable one to judge the different electric furnace designs.

As a comparatively great number of charges are treated in an electric furnace, especially when operating with hot metal, nearly all the furnaces in practical operation today are made of the tilting variety. For this allows the teeming to be accomplished with greater ease, and avoids much trouble caused by the giving away of the tapping hole. Consequently the demand for tilting furnaces today is a general one.

In like manner there is recognized the demand for an easily surveyed and accessible hearth. For, every metallurgical operation will be placed in jeopardy without it. Therefore electric furnaces should have working doors placed at moderate heights above the bath, a little to one side, from which it should be possible to see the entire hearth. This may be required, for instance, in order to exactly determine the condition of the slag, or to be convinced when changing them, that the bath is really

free therefrom before endeavoring to make a new slag. This is entirely independent of the fact that side doors are by far the most advantageous and convenient for charging slag. On account of the absence of an easily surveyed hearth, such resistance furnaces as described in the third chapter, having channels running to and fro, are absolutely to be discarded.

It seems self-evident that we should expect an electric furnace to have its heat, or the necessary appliances required to give it, without influence on the chemical composition of the steel or slag. For it is just by these means that the electric furnace is to prove its superiority over the older gas-heating type. This point is, therefore, to be borne well in mind with every different furnace design. For suppose we assume that at any time during the metallurgical process, for instance, during the oxidation period, the electrical heating should in any way favor the oxidation, then this electrical heat effect would also be present at any other time, *i.e.*, during the reducing period, and the furnace would then consequently be working at a disadvantage. Thus the harm of these effects is often greater than the good they do, as they are also present when they are not wanted.

Every metallurgist will concede that it is justifiable to expect an electric furnace to reach any desired temperature and still avoid any over- or under-heating. That primarily every practically desired temperature must be attainable is evident, when we consider that the electric furnace must enable us to reach the most advantageous temperature for every stage of the metallurgical process. This requirement, therefore, falls together with the one requiring an easy regulation of the incoming energy. With all this, it is of particular importance that the entire furnace contents be heated uniformly, so that over- and under-heating is not to be feared; it is much more likely that there would be an over-heating. The former of these is hardly likely to occur in case considerable heat is carried away by the water-cooled appliances in connection with the electrodes. Borchers, in his 1898 address before the "Verein deutscher Eisenhüttenleute," said:

"As a matter of fact we need not fear that we cannot reach almost any temperature by electrical means for this or that purpose, for we shall have to place much greater weight on guarding against wastefulness on account of working with too high temperatures."

The ninth point requires the electric furnace to be as versatile in its application as possible, and thereby possess the greatest adaptability in order to work it in conjunction with present or future processes. It goes without saying that it would be particularly advantageous for the electric furnace, if it were possible to make in it the greatest variety of steel, equally well and economically, and of the same good quality. For even though one or the other object of making the steel may primarily be the absolutely determining factor, it is still to be noted that the electric furnace has a far-reaching application even today. However, there are at present still many new fields open to its product. So that even though it does not appear to be absolutely necessary, still by far in the most cases it would appear to be advantageous, provided a qualified electric furnace, or some chosen system, fits into the working program equally well for the reception of a new quality, as the previous material did.

The further requirements from the 10th to the 14th are self-evident, if the previous demands made upon the electric furnace are to be fulfilled. As the principal advantage of the electric furnace lies in the fact that it can turn out the highest quality steel from the cheapest raw material, it must consequently be easy to attain the removal of the impurities contained in the charge, provided the electric furnace economically permits whatever refining there may be to do. First, we shall have to concern ourselves with the entire elimination of the phosphorus and sulphur; while removing the impurities which alloy themselves with the iron, (such as copper, for instance,) is also thus so far impossible in the electric furnace. If all the refining possible is to be carried out, it is absolutely necessary that the slag for removing the phosphorus, for instance, can be completely removed from the furnace. For otherwise, when the metallurgical process is continued for the removal of other impurities previously

taken up by the slag, the phosphorus will again be taken up by the molten metal. The requirement of being able to completely remove slag from the furnace is covered, therefore, by doors enabling us to have an easily surveyed and accessible hearth.

It seems just as self-evident that the impurities be removed from all parts of the bath, as it is necessary that all alloys added to it are absorbed equally by all parts of it. Otherwise an uneven material would result. On this account, therefore, a good electric furnace has to have an *adequate circulation*, which assures the greatest uniformity of material in all parts of the hearth. The desired agitation, however, must not exceed certain limits, as otherwise the advantage of the electric furnace would not be used which allows any slag solutions to be separated from the furnace contents.

Finally, in order that the furnace can have a far-reaching application, it is necessary that the furnace be built of such sizes which seem to best fit present or future installations. This is to be kept in mind, for instance, when the furnace is to operate as an adjunct to a converter or an open hearth plant. In such cases, it is, of course, advantageous, if the furnace can receive a whole charge from a converter. It is such reasons as these that make it desirable to build furnaces of the largest capacity.

The 15th requirement exacted a *high thermal efficiency*, and no explanation of this is necessary. However a few words may be said regarding the possible influence of using water cooling. First of all, it is evident that energy losses are caused by every cooling means, and water cooling aids this in the strongest degree, thus lowering the efficiency. Water cooling may become particularly harmful when it is used in such manner as to considerably cool those wall parts which encircle the molten metal. For then the danger arises of the fluid iron assuming a certain tough fluidity, at these places, which makes it very hard to obtain a uniform composition of the entire furnace contents. Finally the employment of water cooling may easily cause dangerous explosions if the devices used are not very well protected. These would occur if the molten metal ever reached the water receptacles

It only remains to mention the last requirements consisting of the lowest installation costs, likewise the lowest refractory cost, and thereby the lowest operating cost which brings together all the exactions which an ideal furnace has to fulfill. Unfortunately, the complete attainment of this ideal has so far not been accomplished by actual practice, as evinced by electric furnace construction. This will be considered in the following chapters, where the constructions, as used, are compared with the stipulated requirements. We will find there, that every furnace design has certain advantages, but also certain disadvantages compared with every other electric furnace design. And it is this which makes the choice of a furnace thus far so difficult, for practical experience and the race in the open market have not yet perceptibly proved the superiority of one or another furnace system.

# CHAPTER VI

## ARC FURNACES IN GENERAL

### THE ARC

If the ends of two current carrying wires are brought together so that the current may flow, and if the two ends are then slightly separated, no interruption of the current will take place. But there will appear a small, highly luminous flame between the ends of the wires, which takes the place of the conductor at the point of interruption. With this, then, we have to deal with an entirely different property from that which the electric spark presents. The latter also represents a current transference through the air. But far higher voltages are necessary for the production of a spark than the arc calls for, an example of which we have just given above. In the latter, it is not the air which bridges the current, but the gases emanating from the metal of the wires between which the arc has been struck. The way the arc occurs then is as follows:

At the instant when the ends of the two wires are separated, a rise of resistance of such magnitude appears at the point of separation, that, with the current flow, a corresponding and important heating effect takes place. It is under this influence that the metal evaporates at the points of contact. If the separation should be increased, then the distance between the wire ends becomes so filled with metallic gases, that these now take up the current transference at the point of interruption. The metallic gases, however, are much poorer conductors than the metal itself. It follows then that the current in its path, from the end of one wire to the other, has to overcome considerable resistance. The current flowing through this resistance gap generates such high temperatures, that more metal is gasified at the gap, in this way maintaining the arc. If no provisions have been made for hand or automatic regulation which keeps the distances between the wire ends constant, then the arc will

rupture itself. This will happen as soon as the distance between the rigid wires is so large that the potential provided is no longer great enough to overcome the resistance of the arc. Should the arc be interrupted and it is desired to create it again, then the same ends of the wire must be brought together again, so that the arc may again be struck.

It may be noticed, when striking an arc, that the metallic gases of the positive wire end or anode are carried away violently. This keeps the metallic gases together in a comparatively contracted area, thus making a definite path for the current.

Even though the conducting metallic gas stream heated as a resistance between the electrodes is absolutely necessary in order to maintain the arc, it can be interrupted by thrusting a cold body into the arc stream, although the maintenance of the arc is being upheld by an entirely permissible distance. When the arc is broken a decided cooling off then occurs at the point of interruption. This phenomenon is also to be considered with the operation of arc furnaces.

From the above it is evident that every arc furnace furnishes that temperature which is required to gasify the conductors between which the arc is to be made. For the gasification of the conductor ends is the hypothesis upon which the maintenance of an arc rests.

The best known arc formation is that which we see in the ordinary arc lamp. Here the arc is usually made between two carbon electrodes.

The arcs in electric furnaces are made in a very similar way, for here carbon electrodes are also used to form the arc. As before said, this arc gives a very high temperature, in fact the highest which has so far been reached; for in the carbon we possess the most resistive conducting material, and this gasifies at about 3500° C. This gives us then the arc temperature with which iron and steel baths are heated in arc furnaces.

Figs. 37 to 39 show the various possibilities which may be utilized for heating metal baths by the electric arc. In the schematically shown arrangement of Fig. 37, where the arc is formed directly between two carbon electrodes, we have the

purest arc heating. The heating of the bath takes place by means of the radiating heat of the arc. The hearth is immediately underneath the arc. These furnaces are generally known today as radiating furnaces. The best known arc furnace using this form of arc heating is the *Stassano* furnace, which will be discussed in detail in the next chapter.

Figs. 38 and 39 show the main idea of two other heating possibilities when using the arc. These methods have the common characteristic of the hanging carbon electrode, which allows the arc to impinge itself directly against the metal. In both of these cases the metal bath is part of the electrical circuit, so that theoretically speaking we no longer have an exclusive arc heating. For the charge, composed of slag and metal,

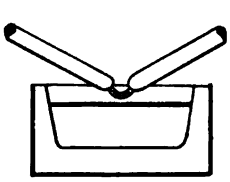


FIG. 37.

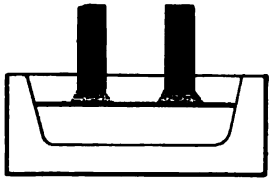


FIG. 38.

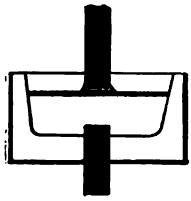


FIG. 39.

naturally offers a certain resistance to the part of the current, by the overcoming of which heat is generated, no matter what the amount may be. Even though the resistance heating of the metal does not practically enter into the question at all, the designation of calling these furnaces *combined arc and resistance furnaces* is at least theoretically correct. Nevertheless these two furnaces have radical differences. The one shown by Fig. 38 has the electrodes of all poles or phases above the bath, whereas with the furnace shown by Fig. 39, one pole is above, the other is constructed in a suitable position below the bath. The best known application of the former possibility is the *Héroult* furnace, whereas the equally well known *Girod* furnace embodies the second qualification.

The question arises, where does the real heating take place, in furnaces as shown by the Figs. 38 and 39, where the arcs impinge directly against the bath?

Although this question is discussed in detail in the chapter on the Girod furnace and an arithmetical example given, still the general answer to this may well be given here, which Borchers gave in 1905 in an address before the "Verein deutscher Eisenhüttenleute." A translation of this follows:

"When the electric current leaves the electrodes, a layer of air, gas or some vapor is formed between the electrode and the slag, which is a heat generating resistance in the circuit. This, therefore, gives us the possibility of arc heating. The bottom surface of the electrode encompasses about 1000 sq. cm. (155 sq. in.), at 3000 amperes. Thus we generate in every second a heat quantity of ($Q = .24\, e\, i$), or say 30 kilogram calories, in the small space between the electrode and the slag, even though we only assume 40 or 50 volts as the arc voltage. This amounts to over 100,000 calories given off hourly from the foot of the electrode. It follows that the slag layer is the second resistance between the electrode and the metal. The heat thus transformed is dependent on the thickness of the slag layer and on its constantly changing conductivity. If we take for this an additional drop of 10 volts, we add an additional 26,000 calories, which is entirely independent *of the small amount of heat appearing in the high conducting iron itself.* The main heat therefore manifests itself in the space between the electrode and the slag. The foot of the electrode thereby has the gasifying temperature of carbon. A very considerable portion of the heat, therefore, enters the bath through radiation and through the carbon vapor, having over 3000° temperature, (C.) which is constantly thrown from the electrode onto the slag surface and is for the most part greedily absorbed by the oxygen in the slag."

From the foregoing general characteristics of the combined arc and resistance furnaces, as they may be alluded to theoretically, it follows that the heating of the metal bath takes place practically almost exclusively through the arc heating alone, so that the above furnaces are fully entitled to be simply referred to as arc furnaces, which is the case in practice.

## THE ELECTRODES

One of the most important parts of all arc furnaces are the electrodes, at the ends of which the arc is maintained, and which lead the current to the bath.

A most resistive material is required for electric furnace electrodes in any event, and only carbon meets the requirements for those coming directly in contact with the bath, (if we omit for the moment the electrodes of iron or conductors of the second class,) as of all the metallic conducting materials, carbon alone stands the highest temperatures. It is, of course, to be considered throughout that carbon is very liable to enter into reactions, especially at the temperatures found in electric furnaces, so that the metal bath must be protected by a layer of slag against an undesirable absorption of carbon, as is done for instance in the Héroult furnace for steel making. If this is done, carbon offers by far the most desirable material for arc furnace electrodes.

These are made in specialty factories, or in case of very large electric furnace installations at their own works. They are made by hydraulic presses, being later on carefully dried and burned. Here one should strive to obtain a complete uniformity of the mass, and the greatest mechanical solidity.

Regarding the electric conductivity, it is to be noted that this varies greatly when using either carbon or the various sorts of amorphous carbon, charcoal, coke or soot. We obtain a higher conductivity, the more the finished electrode approaches the graphitic state, pure graphite electrodes giving the very highest conductivity obtainable. This item is dwelt upon later in detail.

Moving parallel with the increase in the electrical conductivity is the heat conductivity, so that when we have these favorable electrical conditions, *i.e.*, when using graphite electrodes, we have the smallest Joule or $i^2 r$ losses. To be sure, the largest thermal losses occur at the same time, because graphite electrodes, being good conductors, transmit large heat quantities from the inner furnace to the outside.

We then have before us the interesting question concerning the most advantageous composition for the electrodes, *i.e.*, finding out how to gain their best efficiency. This question is of great importance, as the efficiency of the electrodes largely influences the total efficiency of arc furnaces. Before going into this question, however, we will preface it with a few general remarks.

Next to the heat generated in the electrodes, current density has the greatest influence. That is, the number of amperes per unit of electrode cross-section, which of course accompanies the electrical conductivity. In accordance with a paper read before the "Verein deutscher Eisenhüttenleute," by Professor Borchers, in 1908, an electrode material having the conductivity of arc-lamp carbons, commences to gasify its carbon when the current density is from 10 to 15 amperes per square millimetre (6500 to 9750 amp. per square inch), whereas when the current is from .5 to 1.0 amperes per sq. millimetre, (325 to 650 per sq. inch), the temperature attained was from 500 to 600° C.

Of course these current densities just mentioned do not occur in electrodes for electric furnaces. According to A. Helfenstein, the electrodes of calcium carbide furnaces reach a red heat with only 9 to 10 amperes per square centimetre (58.0 to 64.5 amps. per sq. inch). The considerably higher temperatures of carbon electrodes as used in practice in arc furnaces is explained by the electrodes not being heated by their ohmic resistance alone ($i^2 r$ loss), as they are heated besides this by the arc temperature at the electrode end. The following table[1], taken from the book by Wilhelm Borchers, "The Electric Furnace," may show the current densities usually figured with:

| Electrode Diam. | | Carbon Cross-Section per Ampere | | Electrode Cross-Section | | Load in Amperes per Unit | |
|---|---|---|---|---|---|---|---|
| mm. | inches | sq.mm. | sq.in. | sq.cm. | sq.in. | sq.cm. | sq.in. |
| 50 | 1.97 | 10 | .0155 | 19.63 | 3.05 | 10. | 650. |
| 100 | 3.93 | 12 | .0186 | 78.54 | 12.12 | 8.33 | 535. |
| 200 | 7.97 | 20 | .0310 | 314.16 | 50.0 | 5.00 | 325. |
| 300 | 11.90 | 30 to 40 | .0465 to .062 | 706.86 | 111.2 | 3.33 to 2.5 | 215 to 160 |
| 400 | 15.94 | 60 to 90 | .093 to .14 | 1256.64 | 200.0 | 1.66 to 1.11 | 107 to 72 |

[1] The later (1912) type of electrodes used in the 15-ton Héroult furnace at South Chicago are 20 inches in diameter. As they carry from 9000 to 1200 amperes per phase, the current density is as low as 30 to 38 amperes per sq. inch (see also page 307).

It must be seen from the table that the load per unit of cross-section decreases as the electrode cross-section increases, the essential reason being that the manufacture of electrodes of the best quality becomes more difficult as their cross-section increases.

It is also evident, that it is harder to make a completely even mass in a large electrode cross-section, than in a small cross-section. It is likewise much easier to obtain an even annealing for thin electrode rods, than for thick rods. Finally the gasification of part of the binding material of electrodes is much more uniformly and completely accomplished in small cross-sections, than is possible in large cross-sections, in which it is almost impossible to avoid irregularities. If these facts illustrate the decrease of the permissible current density with increasing electrode cross-sections, and if it appears that the use of too large cross-sections is not advisable, we find that the considerable weight of the carbon electrodes is also forbidding; besides there is irregular solidity with growing cross-sections.

Owing to this, it has been found preferable, sometimes, to build up large electrodes of several smaller ones and thus avoid one large electrode block. See Figs. 60*a* and 60*b*.

Thus we can use in these smaller electrodes the higher permissible current densities, and attain a smaller total electrode cross-section, which consequently give the much desired lower thermal losses. With all this, we stand anew before the question of what is the best division between the electrical and thermal losses in the electrodes, *i.e.*, how shall their best efficiency be attained? This theme has been extensively discussed in 1909 and 1911 in the *Electrochemical and Metallurgical Industry*, latterly called *Metallurgical and Chemical Engineering*. The principle articles are by C. A. Hansen and Carl Hering. Even though these dissertations could not solve the question of the best electrode dimensions completely, still, the results are so important that they are presented here in condensed form.

As before mentioned there are two kinds of losses in the electrodes:

1. *Losses through Joule heat, i.e.*, those in consequence of the electric current flowing.

2. *Losses through heat conduction, i.e.*, those occasioned by the electrode (being a good heat conductor) leading the heat from the inner furnace to the outside.

How complicated these conditions become by the cooperation of these two losses is evidenced by one of Hansen's tests, for he obtained the astounding result, when the ohmic resistance and the current density were increased to such an extent that the Joule losses doubled—still the total losses remained the same.

Of what importance the clearing up of these conditions is, is very evident, when we hear that according to Hansen the losses in a furnace operating with 500 Kw. can easily be 15 per cent. of the total energy input. This would be continually 75 Kw., or with a current cost of ¾ cent per Kw.-hour, the electrode losses would cost about 56 cents hourly.

When the electrodes are incorrectly dimensioned, it may happen that thermal losses increase to such an extent, that it is no longer possible to keep the whole bath molten. Then only just that part which is directly beneath the arc will stay molten, while the remainder will remain solid, owing to the heat transference occasioned by the extravagant dimensioning of the electrodes.

These examples already show that a saving in the electrode losses may, under certain circumstances, be the deciding factor for the economic working of the electrode furnace, especially if the price of current be high, while in other cases large sums of money could be saved, if we succeeded in approaching as nearly as possible the best theoretical electrode dimensions.

In order to become acquainted with the conditions governing the least losses, Hansen made parallel tests with graphite and carbon electrodes which gave the following results.

The efficiency of graphite electrodes grows with increasing length and increasing current densities. It is, however, impossible to force the current density above certain limits, as the electrodes then taken on temperatures that are too high, which might easily destroy the surrounding brickwork.

With ordinary carbon electrodes an increasing length causes a decrease in the efficiency, whereas the Joule effect becomes much larger than the thermal losses.

The experimentally ascertained conditions of Hansen are, of course, only true between certain limits. It is evident that by continuing to increase the length of graphite electrodes, up to a certain point, a condition would soon result where the losses are a minimum. If this point is exceeded then the Joule effect would increase more rapidly than the heat losses would decrease, and this would result in an increase of the total losses.

Similarly the minimum losses would be exceeded if the current density were increased beyond its best value.

These reflections led *Hering* to determine the most favorable electrode dimensions theoretically. Even though these determinations do not always give the greatest consideration to the conditions in actual practice, and the results may only be partly used in practice, still they give such interesting disclosures, regarding occurring conditions, that they are for this reason worthy of note, and will be given a little later on.

Now next it is evident, that under any conditions and independent of material, an increase in the electrode cross-section increases the heat conducting losses, simultaneously, though decreasing the electrical losses. On the other hand a lengthening of the electrode, namely on the inside of the insulating brickwork, causes a decrease of the thermal and an increase of the electrical losses. When both cases are extreme the losses will be infinitely great.

It is a fact, however, that the Joule heat as well as the heat carried off through conduction are both generated by electricity. Thus the object is to bring the total losses down to a minimum.

For this it is quite necessary to know accurate values of heat conductivity and specific resistance for every electrode material. Furthermore, there should be accurate results on the independence of these values of the temperature. Unfortunately such results are almost wholly missing. To all this must be added the fact that all electrodes are manufactured articles, which are not capable of being produced of complete uniformity, and the constants of these, (of proved material,) are greatly dependent on the chosen cross-section.

On account of all these reasons, these figures, ascertained

from the present meagre tests, cannot lay any claim to general validity. Therefore, the following values must also be cautiously used and should be considered primarily as approximate values.

*Hering*, in his computations, now entirely neglects the heat quantity which is given off by the electrode, and which is absorbed by its surrounding brickwork. He assumes that the electrode is insulated throughout its entire length, so that the heat is only conducted away by the end of the electrode, which is on the outside of the furnace and there usually cooled with water. He further assumes that the electrode has the exact same cross-section throughout its entire length, and that the change of conductivity with temperature follows a straight line. All these are assumptions which are not borne out by the facts, but are, however, necessary in order to make the conditions for theory and practice more distinguishable.

With the assumptions as made, the conditions may be visually shown by Figs. 40 and 41. In Fig. 40, *E E* represents

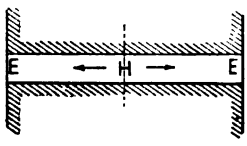



FIG. 40.

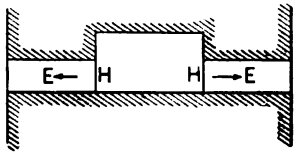



FIG. 41.

an electrode, which is surrounded about its periphery with a complete heat insulator, so that only the ends remain free, which are for instance kept cool by means of water-cooling. If we now send a comparatively heavy current through the electrode, this will heat the latter strongly at the middle point *H*, until an equalizing condition occurs. As soon as this is reached, the entire Joule heat will be carried off at the cooled electrode ends, while no heat flow will occur at *H* any more.

If we now cut the insulated electrode at *H*, in order to utilize both parts as electrodes for an electric furnace, as it is schematically shown by Fig. 41, there will be no change in the situation, provided the furnace has the same temperature which it formerly

had at $H$, assuming of course that the same current strength as before now flows through the electrodes. Under these conditions also, there will be no heat loss from the furnace interior, through the electrodes to the outside of the furnace.

The condition given herewith is the ideal one, so that we may have only the minimum electrode losses, with, of course, the previously made assumptions.

Provided the assumptions have the limitations as originally laid down, the losses will be equal to

$$Q = Q_1 + \frac{Q_2}{2}$$

where $Q_1$ equals that heat loss, which would be carried from the furnace to the outside by the electrode, if no electric current were flowing, and $Q_2$ equals that heat quantity which is solely and alone generated by the current overcoming the electrode resistance $= i^2 r$.

$$\text{Consequently } Q_1 = c\, k\, \tau \frac{q}{l}$$

here $c = 4.18$, a constant, which is used for converting gram calories into watts.

$k$ = the mean conductivity in gram calories per second by 1 cm. length and 1 sq. cm. cross-section, with the temperature difference appearing between the hot and the cold electrode ends.

$\tau$ = temperature difference between the hot and cold electrode ends.

$l$ = the length of the electrode in centimetres.

Furthermore,

$$Q_2 = i^2 r = i^2 \rho_1 \frac{l}{q}$$

where $r$ denotes the total resistance of the electrodes.

$\rho_1$ = the mean specific resistance per cubic centimetre at the occurring temperature difference.

$l$ = length in centimetres.

$q$ = cross-section in square centimetres.

We therefore obtain the total losses, which are carried away from the cold electrode, as

$$Q = Q_1 + \frac{Q_2}{2} = 4.18\, k\, \tau \frac{q}{l} + \frac{1}{2} i^2 \rho_1 \frac{l}{q}$$

that is:

*The total energy losses carried off at the cool electrode end, are equal to the sum of the heat losses, which would occur if no current flowed through the electrode, plus half of the heat lost by means of the Joule effect.*

The losses are a minimum when the pure heat losses are equal to one-half those caused by the Joule effect, *i.e.*, when

$$4.18\, k\, \tau \frac{q}{l} = \frac{1}{2} i^2 \rho_1 \frac{l}{q}.$$

In this case the total losses are equal to the Joule heat losses or $i^2 r$, and hence no heat would be carried from the furnace by conduction.

From the equation for the minimum losses,

$$4.18\, k\, \tau \frac{q}{l} = \frac{1}{2} i^2 \rho_1 \frac{l}{q}$$

it follows that

$$\frac{q}{l} = .345\, i \sqrt{\frac{\rho_1}{k\, \tau}}$$

If this result is then substituted for $\frac{q}{l}$ in the general equation for the total losses, we have:

$$Q = 4.18\, k\, \tau \frac{q}{l} + \frac{1}{2} i^2 \rho_1 \frac{l}{q}.$$

In order to attain the minimum losses we have the requirement

$$Q_{min} = 2.89\, i \sqrt{k\, \tau\, \rho_1}$$

The equation for $Q_{min}$ shows that the minimum losses are determined by the material constants $k$ and $\rho_1$, the temperature differences between the hot and cold electrode ends, and the current strength. It is independent of the absolute dimensions of the electrodes, for of these it is only required to maintain a definite relation between the cross-section and the length in accordance with the equation for $\frac{q}{l}$.

If we substitute for the equation for $Q_{min}$ the specific conductivity per cubic centimetre, $\kappa = \frac{l}{e}$, in place of the specific resistance, we obtain

$$Q_{min} = 2.89\, i \sqrt{\frac{k}{\kappa}\tau}$$

This equation shows that the least losses are fixed for a certain definite temperature on account of the relation between the heat conductivity and the electrical conductivity. *In accordance with this the best material for the electrodes is that which has the least heat conductivity and the highest possible electrical conductivity.*

From the equation for the minimum losses, it follows that an increase of the temperature difference between the hot and cold electrode ends only influences the losses in proportion to the square root of these differences.

If we again consider the equation,

$$\frac{q}{l} = .345\, i \sqrt{\frac{\rho_1}{k\tau}}$$

we see, that with a given material, a given current strength, and a given temperature difference, the electrode losses would remain the same for entirely different cross-sections, provided the proportion between the cross-section and the length remained unchanged.

From this we now learn: *If it be desired to save on electrode material when having a minimum of losses, then the electrode is to be made as short as possible.* Generally the electrode length is primarily determined by the practical demands of the furnace operation, so that a certain minimum distance of electrode length cannot be exceeded. The length of electrode, therefore, having been determined, the cross-section can be calculated by using the formula $\frac{q}{l}$.

It is well to mention here that it can be assumed that all these calculations only retain their full correctness, provided the electrodes are protected by insulation throughout their whole length. If this assumption has to be dropped, which is necessary for practical purposes, then an increase of the cross-section in

the same proportion to the length, causes a decided increase in the electrode surface and with it naturally an increase of the heat losses.

From the derived formulas, it is evident that the current strength influences the size of the losses. Consequently, it would be requisite to have the smallest possible current at high voltages. Unfortunately, this demand cannot be fulfilled, without leaving the total efficiency of the furnace out of consideration, for it is always well to keep in mind that the electrode losses considerably affect the furnace efficiency, but are not the sole factors that carry weight with it. This point is discussed further on.

In place of the current strength in the formula

$$\frac{q}{l} = .345\, i \sqrt{\frac{\rho_1}{k\tau}}$$

we can insert the current density $\Delta = \frac{i}{q}$,

and obtain

$$l = 2.89 \frac{I}{\Delta} = \sqrt{\frac{k\,\tau}{\rho_1}}$$

This formula produces a combination showing the best conditions between cross-section and length together with a current density fit for use. This seems advantageous, because by overstepping the permissible current density limits, it is very easy to endanger the furnace operation. On page 84 mention has been made of these tests by *Hansen*. However, this formula also has the disadvantage, that it determines the electrode length arithmetically, which is not fully determinable for practical reasons. And the value of this derived formula, practically only consists in bringing forth a clear idea of the conditions of an ideal case. It should be the ambition of every furnace designer to come as near to this as possible.

In order to be able to utilize these rules and references, it would be necessary to have useful constants for the different conductivities of different electrode materials. Unfortunately there has been a great lack of these up to the present. Even though a few values are given hereafter, it must be observed that they have reference only to a certain definite material, which just

happened to be used for these determinations, and that products from other factories would give results deviating from these, more or less. Nevertheless, the figures comparing the graphite and carbon electrodes may be regarded as typical, and can consequently be used in practise for electrode designs.

*Hansen* gives the following figures for temperature differences up to 3000° Centigrade:

| Material. | $\rho_1$ | $k$ |
|---|---|---|
| Graphite[1] | .000812 | .16 |
| Carbon[2] | .00183 | .016 |

*The proportion between the electrical resistance of carbon and graphite is as* 2.25 : 1, *whereas the heat conductivity of graphite is ten times as great as that of carbon.*

Relative to the current densities *Hansen* believes it safe to figure with the following values:[3] For graphite, 150 amps. per square inch. This equals 4.3 sq. mm. per amp. or 23.25 amp. per sq. cm. For carbon, 50 amp. per square inch. This equals 13 sq. mm. per amp., or 7.75 amp. per sq. cm. Substituting these values in the ratio $\frac{q}{l}$ in accordance with the equation:

$$\frac{q}{l} = .345\, i \sqrt{\frac{\rho_1}{k\,\tau}}$$

for instance for 20000 amp., and 3000° C., we have for graphite,

$$\frac{q}{l} = .345 \times 2000 \sqrt{\frac{.000812}{.16 \times 3000}} = 9.0$$

and for carbon,

$$\frac{q}{l} = .345 \times 2000 \sqrt{\frac{.000183}{.016 \times 3000}} = 42.57$$

*i.e.*, for equal electrode lengths (which would be required for the same furnace) of graphite as well as for carbon, a *carbon electrode would have to have* $\frac{42.57}{9.} = 4.73$ *times the cross-section of a graphite electrode.*

---

[1] Specific resistance ohms per inch cube = .000320.

[2] Specific resistance ohms per inch cube = .000721.

[3] Compare the values dependent on the cross-section as given on page 82. See also page 81.

After the relation for $\frac{q}{l}$ is given, we can either assume the required electrode length as given (on account of the practical furnace requirements), and thereafter determine the cross-section, which could then be regulated by permissible current densities. We could, however, also figure from a given current density as a basis, and from the cross-section thus determined, calculate the electrode length, which would then have to have its practical applicability proved.

Should we choose the latter method, we may calculate the cross-section based on a certain current density deemed permissible, and based on Hansen's values, for instance, for the electrode cross-sections of this material. The example cited was for 20,000 amperes. We then have:

$$\text{graphite} = \frac{20000}{23.25} = 860 \text{ sq. cm.}$$

$$\left(= \frac{20000}{150} = 133 \text{ sq. inches}\right)$$

on account of the proportion, therefore, of $\frac{q}{l} = 9$, we obtain a length of 95 cm., or 37.4 inches.

If we assume that this length is satisfactory to the furnace operation, then this same length will, of course, have to be kept for the carbon electrode, and in case a minimum of losses is also desired here, we would have for the carbon electrode cross-section (based on the calculated relation of $\frac{q}{l} = 42.57$)

$$q \text{ carbon} = 4044 \text{ sq. cm.}$$

$$(= 1591 \text{ sq. inches}).$$

From this, with 20000 amps., we have a current density of

$$\Delta = \frac{20000}{4044} = 4.9 \text{ amp. per sq. cm.}$$

$$\left(= \frac{20000}{1591} 12.5 \text{ amp. per sq. in.}\right),$$

which would show that according to the values given on page 82, these are sufficiently high, so that an enlargement of the cross-section would recommend itself, and perhaps a simultaneous

increase in the electrode length, in order to stay as close as possible to the minimum losses.

Besides this it is interesting to become acquainted with the losses as they appear in the given example, either when using graphite or carbon for the electrodes. The equation for the minimum losses was:

$$Q_{min} = 2.89\, i \sqrt{k\, \tau\, \rho_1}$$

By substituting the values for graphite, we obtain $Q_{min} = 36$ KW and for carbon $Q_{min} = 17$ KW., *i.e.*, assuming that the given constants are correct, the losses for graphite would be about twice as large as those for carbon.

This condition, however, only holds good, when the electrodes are heat insulated for their entire length as previously mentioned.

In accordance with the values heretofore cited on page 82, for the usual current density values for electric arc furnace carbon electrodes, it seems that the figure of 7.75 amps. per square centimetre (50 amps. per square inch), which Hansen gives, is extraordinarily high. It is therefore not advisable to use these figures, which gives much too short electrodes for practical furnace constructions, as the example showed. It is better to use those values given on page 82, which simultaneously take into consideration the influence of the electrode cross-section enlargement.

The figures given in the following tables are from tests made by Hansen and published by him. On the one hand for graphite electrodes made by the International Acheson Graphite Co., and on the other for carbon electrodes made by the National Carbon Co.; these may show the influence of the cross-section enlargement on the material constants even a little better.

ACHESON GRAPHITE ELECTRODES

| Diameter or Cross-Section | $\rho_1$ = Resistance ohms per cm. cube | Diameter or Cross-Section | $\rho_2$ = Resistance ohms per in. cube |
|---|---|---|---|
| 5.08 cm. diam. | .00092 to .00093 | 2 inches diam. | .000362 to .000366 |
| 7.62 cm. diam. | .00103 to .00109 | 3 inches diam. | .000406 to .000429 |
| 10.16x10.16 sq.cm. | .00096 to .00101 | 4 in. x 4 in. | .000378 to .000397 |
| 15.24x15.24 sq.cm. | .00084 to .00085 | 6 in. x 6 in. | .000331 to .000335 |

These measurements were made at a temperature of 25° C. With increasing temperature the resistance of graphite falls as is well known. According to *Hansen*, this is as follows:

| | | | |
|---|---|---|---|
| At | 25° | Centigrade..... | 100% |
| " | 400° | " ..... | 94% |
| " | 800° | " ..... | 81.5% |
| " | 1200° | " ..... | 66% |
| " | 1600° | " ..... | 65% |
| " | 2000° | " ..... | 68% |
| " | 2200° | " ..... | 69% |

For carbon electrodes *Hansen* found the following values depending on the cross-section:

NATIONAL CARBON COMPANY ELECTRODES

| Size of Cross-Section | $\rho_1$ = Resistance in ohms per ccm. cube | Size of Cross-Section | $\rho_2$ = Resistance in ohms per inch cube |
|---|---|---|---|
| 10.16x10.16 sq.cm. | .00457 | 4 in. x 4 in. | .00180 |
| 15.24x15.24 sq.cm. | .00856 | 6 in. x 6 in. | .00337 |
| 20.23x20.23 sq.cm. | .00594 to .0071 | 8 in. x 8 in. | .00234 to .00279 |
| 45.72x45.72 sq.cm. | .014 to .0254 | 18 in. x 18 in. | .00551 to .0100 |

Referring to the last of these values, it is well to note that this test was made on an electrode delivered 4 years ago, and it is possible that better results have been attained since then, for large electrodes.[1]

*Hansen* also made some investigations with carbon electrodes in order to determine the influence of temperature. He found that, with an increasing temperature, the carbon continually proceeded to graphitize, so that after the electrodes had cooled down, the original figures for the specific resistance no longer held true, but were, instead, much better.

The following table shows how the specific resistance of the cold carbon electrode falls, in case the electrode has been previously heated to the temperature shown in the table:

[1] In 1912 the National Carbon Co. state that their "Steel furnace electrodes have a resistance of about .0025 to .0030 ohms per inch cube."

| | |
|---|---|
| Resistance in the cold condition..... | 100% |
| After heating up to 1200° C..... | 91·6% |
| " " " 1600° C..... | 87·% |
| " " " 2000° C..... | 77·6% |
| " " " 2400° C..... | 65·9% |
| " " " 2800° C..... | 50·9% |
| " " " 3500° C..... | 22·4% |

Here the last figure approaches that which would be obtained with graphite electrodes under the same conditions.

Besides, *Hansen* gives as an average figure of many tests made with commercial carbon electrodes when heated to 1200° C., a resistance value equal to 60 per cent. of that measured in the cold state.

After the electrodes have once been in operation, the uniformity of the material constants disappear in all parts of the cross-section or the length, owing to the uneven heating of the carbon throughout its entire length. On this account Hansen takes the practical resistance at 1200° C., at only 40 per cent. of its cold figure.

As for the rest, we again point to the figures which were used in the arithmetical example on page 76.

The remarks regarding the best dimensioning of the electrodes, have a certain practical significance, and that is why they have been discussed here. It is well to be warned, though, that too great stress be not placed on these theoretical opinions.

It is to be noted that the derived formulæ are only strictly accurate for such cases, where the electrode is protected from heat losses between its hot and cold ends and that this case never appears in practise. It is further to be observed, that the operation of our arc furnaces necessitates a shortening of the electrodes, and consequently considerable electrode lengths appear, which are not taken into consideration in the formula, because they lie outside of the water cooling. Furthermore, the formula are not the only measure for the losses which actually appear in arc furnaces, irrespective of the restrictions just made. Besides the pure radiating losses, there are for instance the contact losses, where the current carrying copper conductor clamps onto the

electrode. And above all it is a noticeable fact, that on the one hand, the size of the cross-section is of the greatest influence on the efficiency of the furnace, while on the other we see that the electrode length is primarily settled by practical considerations accompanying the furnace operation.

We see, therefore, that just this relation between cross-section and length of electrode, which is of striking importance in accordance with the formula for the minimum losses, cannot be freely determined according to the arithmetical values. After all, the benefit of the calculation for the minimum losses lies in the fact that it allows us to ascertain the heat dimensions which lie between the given limits of practical requirements, that we may come as near them as possible.

Turning again toward the practical side of the electrode question, we find an interesting work of *Hansen's*, which deals with the *burning away of the electrode or electrode consumption.*

This question is, of course, of equal importance, as the striving after the least electrical losses, or a high efficiency; for this point is of considerable influence on the operating costs.

The consumption of electrodes may occur:

1. In the worst case when the electrode breaks;

2. By the arc formation which causes a gasifying of the carbon and

3. By oxidation.

Those under the first heading, which are by far the most unpleasant, seldom or never occur today, as long as the cross-section and lengths used are not too large. Too large cross-sections are always to be avoided, so that if high currents cannot be avoided, it is better to use graphite in place of carbon electrodes. Furthermore, it is to be observed that a new electrode must not be placed in the hot furnace in its cold state, as small particles are easily liable to crack off, on account of the great prevailing temperature differences. It is therefore commendable to heat the electrodes slightly before placing them in use.

The losses under the second heading are self-evident and unavoidable, so that nothing remains to be said about them.

On the contrary a much greater interest manifests itself in the *electrode consumption on account of the oxidation.*

*Moissan* found that amorphous carbon commences to oxidize at as low a temperature as 375 to 490° C., whereas graphite first begins to oxidize at temperatures of 665 to 690° C. These values though were observed with powdered material and not with solid rods.[1] Finally, *Collins*, *FitzGerald*, and *Johnson* maintain that graphite possesses a greater resistivity against oxidation than carbon does.

Contrary to this, *Hansen* observed that the losses with graphite electrodes are greater than those with carbon electrodes. In making these tests, graphite rods of the *International Acheson Graphite Co.*, and carbon rods of the *National Carbon Co.* were used. The reason for the higher consumption, when using graphite rods, as given by *Hansen*, is that at temperatures of 1300 to 1400° C., the graphite particles cracking off are so large, that some of them could be picked up unconsumed. This phenomenon disappeared when the heating occurred in carbonic acid gas, which proves that the cracking off, of the electrode particles, when using graphite, leads us back to the oxidizing influence.

This investigation shows that it is impossible to accurately determine in advance just what the electrode consumption will be. For this is so dependent on all oxidizing influences, that even the tight or less tight closing of the working doors, or the piercing of the electrodes through the furnace roof, or the working in a more or less reducing atmosphere, may cause considerable changes in the electrode consumption.

Oxidizing losses not only affect the electrode consumption, but the power consumption of the furnace as well, *i.e.*, the efficiency. This is evident from the following tests.

*Hansen* operated a small Héroult furnace of 150 kg. (330 lbs.) capacity, with graphite electrodes of 10.16 x 10.16 sq. cm. (16 sq. inches) cross-section and 106. cm. (40 inches) long.

[1] These values, however, seem quite reliable since we find data published from electrode manufacturers which give the temperature of oxidation in air at 640° C., and 500° C., respectively, for graphite and carbon.

With this arrangement he succeeded in melting a 150 kg. charge with 150 kw.-hrs.

Later on a similar furnace was operated, but for 300 kg. (660 lbs.), having the same electrodes. It was established here through various tests, that the power consumption of the larger furnace had the ratio of 1.2 to 1 compared to the smaller furnace, even though a larger furnace usually has comparatively smaller thermal losses than a smaller furnace. After graphite electrodes of 15.24 x 15.24 cm. sq. (36 sq. inches), and 101.6 cm. (40 inches), long were used, the larger furnace gave a somewhat better power consumption than the smaller one.

The tests further showed that the power consumption rose, as soon as the electrode (the end toward the molten metal) became more and more pointed under the oxidizing influences. The difference in power consumption when working with the full cross-section compared to the operation with a pointed one was as much as 30 per cent.

This test, as well as others made with various electrode cross-sections in the 300 Kg. (660 lb.) trial furnace, show that a larger cross-section causes a decrease in the losses. This may be primarily caused by the fact that a larger cross-section permits a more favorable dissemination of energy throughout the whole charge, and furthermore, because the full and larger electrode cross-section acts as an umbrella, which considerably lessens the heat radiation toward the furnace roof. The umbrella action of the electrode also has the additional advantage of keeping the roof from deteriorating too rapidly. This, however, changes as soon as the electrode takes on its pointed form.

*Hansen* established that a more or less strong sharpening to a point of the electrode occurs in all arc furnaces, under the oxidizing influence which takes place during the working period. The trials carried out to protect the electrodes by suitable coverings of carborundum, water-glass, etc., against the oxidation, have not been successful, for it has not been possible to make the covering durable with the prevalent temperature differences, occurring during the furnace operation. We, therefore, have to figure with a certain burning away of all electrodes, owing to the oxidation.

Aside from the three reasons, which have so far been given to determine the electrode consumption, there must still be mentioned the additional loss caused by the stub ends. The length of this stub end depends largely on the distance between the molten metal and the furnace roof. Recently newer methods have been devised which now render it possible to attach the electrode remainders to the new electrodes, thus assuring a most complete use of the electrode material. This is gone into further in the chapter on the Héroult furnace.

During the discussion of the electrode conditions, we have often compared the graphite with the carbon electrodes. Is therefore one recommended above the other? To this question this reply may be given: Graphite electrodes mainly have the advantage of greater resistivity, and greater mechanical firmness. This advantage, though, must be purchased at a far higher price, compared to carbon electrodes. Large electrode surfaces tend to save energy, and consequently it is better to work with low current densities. For the graphite electrode loses its importance, *i. e.*, its high electrical conductivity, whereas its disadvantage of a high heat conductivity falls heavily in the balance, so that the graphite electrode always has a lesser efficiency than the carbon electrode (see page 94).

From all this it is apparent, that one would at first endeavor to utilize carbon electrodes, at least as long as these can still be made of good quality and at the desired cross-sections. It is only with the largest furnaces, where the cross-sections would become so large, that uncertainties would enter the operation, through breakages, for instance, that one would be willing to pocket the disadvantages of the graphite electrode, in order to gain the important advantage of definite and sure operating conditions.

## THE ELECTRODE COOLING

Previously when discussing electrode conditions it was always assumed some water cooling would be arranged at the place where the electrode leaves the furnace roof, by means of which it would be possible, to lower the temperature of the

electrode as much as 100 or 200° C. It was also shown that the electrode material may occasion considerable losses on account of the oxidation, and this gives us the first reason which forces the application of electrode cooling upon us.

If sufficient cooling was provided, so that the electrode, where it issues from the furnace, is not cooled below the temperature, where the oxidation begins, then the unavoidable oxidation in the circulating atmosphere would considerably reduce the cross-section. This would be followed by an increase in the electrical resistance, hence a stronger heating up of the cross-section already weakened, and therefore an increasing temperature with increasing consumption, so that in the shortest space of time a change of electrodes would be required.

If an intensive water cooling is already unavoidable, this will simultaneously act protectingly on the uniformity of the furnace operation. Thus the contact arrangements which connect the copper conductors to the carbon electrodes are kept from being destroyed. Supposing we assume that the electrode, even outside the furnace, has a comparatively high temperature as well, then there would be such an increase in the heating of the contact pieces, that their hold on the electrodes would be loosened, and with other designs they would burst, so that in both cases the furnace operation would fail, on account of a break in the electrode contacts, quite irrespective of any damage done by the flames shooting through the roof, where the electrodes enter.

The water-cooling device is also responsible for the long life to-day of the arc furnace contact clamps. At the same time, it fulfils a third and very important purpose. It was shown in Chapter II that all refractory materials used in electric furnace construction are conductors of the second class, and as such obtain higher conductivities with increasing temperatures. This also holds for the brickwork between which the electrodes of arc furnaces lie. It is apparent that these roof bricks become more and more conducting with increasing temperatures, whereas they can be regarded practically as non-conductors with low or even moderate temperatures. In order to avoid a strong oxidation

of the electrodes, and to attain the best possible thermal efficiency, it is necessary to have the closest fit where the electrodes protrude through the furnace roof. Thus, it is immediately apparent, that when the roof refractories are little resistant, *i.e.*, when their temperature is high, then the small spaces between the electrodes and the surrounding roof bricks are easily bridged over with tiny arcs, which in turn cause currents to flow through the refractory material from one electrode to the other.

The current flowing through the brickwork will be higher, as the voltage increases between the different electrodes, as the distance between the electrodes becomes less and the temperature of the brickwork between the electrodes rises. That these currents flowing through the refractory material may be of great importance is shown in an article by Coussergues after seeing a Stassano furnace. In a one-ton furnace, when the arc was interrupted and the voltage was 120, there was still a current of 300 amperes flowing through the brickwork from electrode to electrode. It is to be noted here, that the entrance of the electrodes to the furnace is provided with water-cooling contrivances. If an attempt were made in such a case as this, to do away with the water-cooling, then the temperature of the brickwork in the neighborhood of the electrodes would rise considerably, the resistance between electrode and electrode would thereby further decrease, and still stronger currents would traverse the brickwork. The result would be a considerable increase in the energy consumption, while a strong heating ensues at the wrong place, and at the same time there would be a quick destruction of the very highly heated roof due to the current flowing.

In accordance with the foregoing, it is established that the utilization of water cooling with arc furnaces offers important operating advantages, even though there is, of course, a certain heat loss on that account, which is unavoidable up to certain limits. Aside from this there is still, under some circumstances, a small electrical loss, which may appear when currents from the electrode find their way to the cooling chambers, and are thence grounded by the water.

## THE ELECTRODE REGULATION

In discussing the arc it was shown that it can only be maintained, provided a certain distance between the electrode and the bath is not exceeded, as otherwise the arc will be interrupted. It is therefore necessary to watch the length of the arc. This is easily accomplished with the aid of a voltmeter or an ammeter. The electrodes are then regulated in accordance with readings of the controlling instruments.

Even though a manually operated regulation of the electrodes is possible, as, for instance, with the Stassano furnace, we find the equipment with automatic regulation, as used in the arc furnaces of Héroult and Girod to-day, have several advantages.

In both cases, *i.e.*, either hand or automatic regulation, this is accomplished with the aid of gears, which are driven by an electric-motor in order to handle them faster and more accurately. In accordance with the indications on the measuring instruments the motor is started either to the right or left by throwing a double-throw switch, which either raises or lowers the electrode.

The *Thury regulator*, invented in 1898, is used almost exclusively for this automatic regulation. It is made by *Ateliers H. Cuénod, A.G.*, at *Chatelaine* near Geneva, Switzerland.

The principal part of a Thury regulator is an electro-magnetic scale, which is balanced when the current and voltage conditions are normal. When deviations occur in the normal circuit conditions, they throw the lever out of balance. These scales are used then to throw a switch to either one side or the other, so that the current for the driving motor enters it either from one or the other side, thus bringing about the corresponding motion of the electrode.

The switching mechanism of the Thury regulator consists of a small constantly running auxiliary motor, which moves a lever back and forth. This lever engages a suitable pawl and ratchet mechanism so arranged, that when the electro-magnetic scale is not in balance, it releases one of two pawls which then catches the teeth of a wheel, and causes it to revolve in one direction or another, by the aid of the pendulum motion of the lever, carrying the pawls, at the same time the shaft of this latter wheel carries

the switch, which operates the driving motor. Fig. 42 shows this mechanism.

The electro-magnetic scales which bring about the desired regulation, are built for either direct or alternating current. It operates as a volt, ampere, watt or ohm meter and is provided

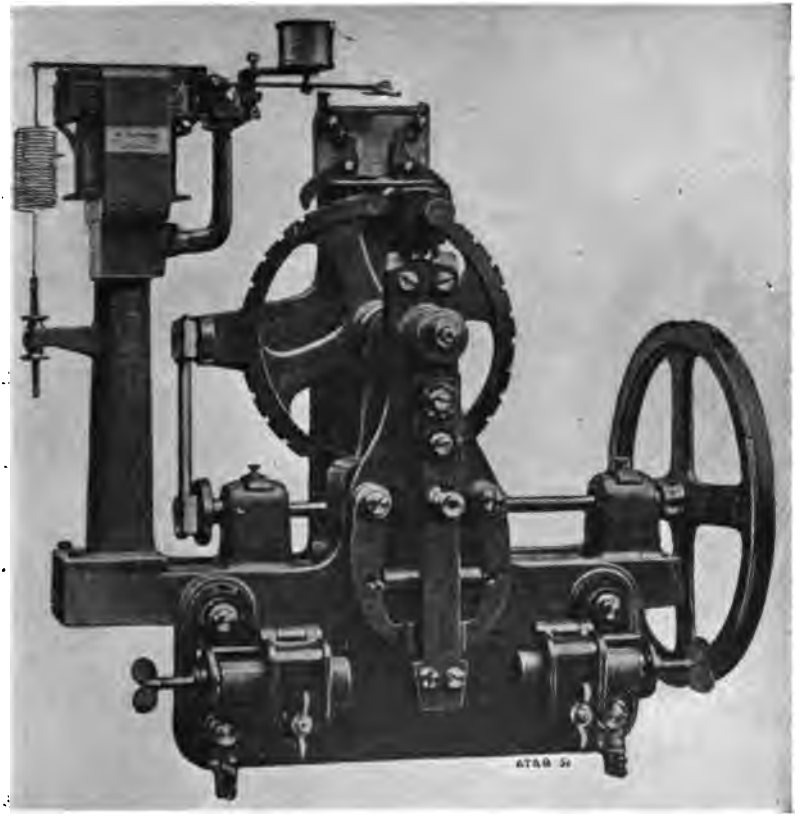


FIG. 42.

with a regulating resistance, which allows the operating conditions of the furnace to be changed at will. The double-throw switch, which controls the driving motor is either single or double pole. The current is broken between an adjustable copper piece and a block of carbon of generous dimensions, so as to equalize the burning away of the contacts, or to lengthen the time of contact.

If several furnaces are to be automatically regulated, only one driving motor is required for all regulators. The apparatus are then mounted on a switchboard, which also carries the control instruments such as volt and ammeters.

The regulators are also provided with a manually operated switch, which cuts out the automatic regulation, so that hand regulation may be resorted to. The motor drive for the pulleys

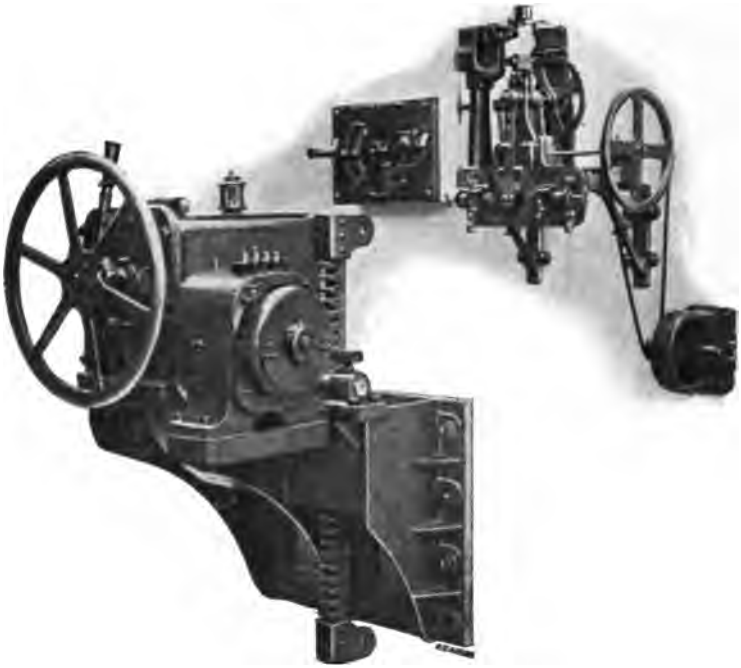


FIG. 43.

is kept, however, which is often very desirable when using hand regulation.

Fig. 43 shows an assembled view of all the apparatus, which is necessary for an automatic regulation of the electrodes. There is a train of gears, of which a pinion and rack either raises or lowers the electrodes. The electrodes may also be suitably set by the aid of cables or chains. The weight of the electrode and its appurtenances may be partly equalized by a suitable counterweight.

The foregoing has briefly discussed the more or less common phenomena and appliances of arc furnaces, and hereafter some of the various designs of arc furnaces will be gone into. The most important things of arc heating may again be briefly stated here.

In all arc furnaces the heating of the bath is brought about practically exclusively by the arc itself. There are always temperatures of about 3500° C., occasioned by the arc. Even with a moderate heating this temperature cannot be avoided.

*Borchers*, in his 1908 address before the "Verein deutscher Eisenhüttenleute," said about this:

"In arc furnaces there may be many arcs, the arcs may also be brought in more or less great distances from the bath, in order to bring this to a temperature of less than 3500° C.; but 3500° C. is always generated at some restricted places, and we must operate downwards from this temperature."

# CHAPTER VII

## THE STASSANO FURNACE

It was shown in Chapter VI, that among the better known electric furnaces, the Stassano furnace is the only one which is exclusively operated by arc heating. We may, therefore, also refer to it as a radiating furnace.

It was *Stassano's* original ambition to build an electric blast or shaft furnace. His object was primarily to use profitably the rich ore fields of Italy, where native coal is scarce.

His first patent, issued in 1898, in England, is based on the following claim: "The utilization of caloric energy of the voltaic arc for primary determining the reduction of oxide of iron and the metals to be combined therewith and afterwards melting the metallic masses reduced, for the purpose of obtaining in a fluid state the product desired, all substantially as set forth."

The furnace which *Stassano* suggested for this trial is shown by Fig. 44 in plan and vertical cross-section. Without describing the first design of this furnace at length, it may be briefly said, that Stassano laid great stress on the point that no air was permitted to enter the furnace. With a furnace of this kind Stassano made his first tests in Rome. With 1800 amperes at 50 volts he succeeded in producing 30 Kg. (66 lbs.), of metal in one hour.

As a result of these trials, a furnace plant for the direct reduction of iron ores was erected at *Darfo*, in Lombardy, *Italy*.

Despite several changes in the construction of his furnace, Stassano, though keeping his method of heating, was not able to give any permanent life to his electric shaft furnace. When the Canadian Commission made their observation trip in 1904 the installation at Darfo was no longer in existence.

In the meantime, Stassano had forsaken the original design of the shaft-like construction, and instead built a hearth furnace

with an inclined bottom as shown in Figs. 45 and 46. This furnace in which the ore was charged underneath the arcs, in-

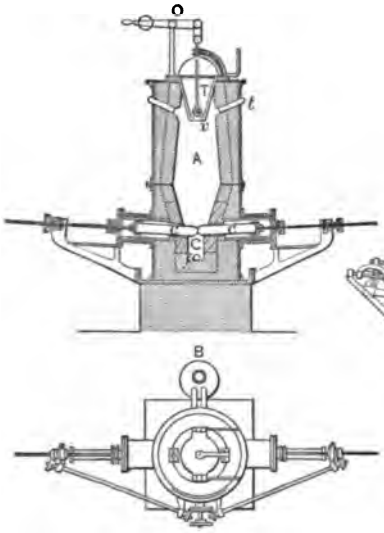



FIG. 44.

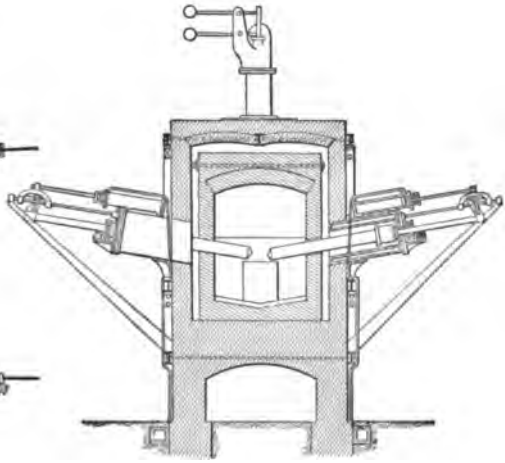


FIG. 45.

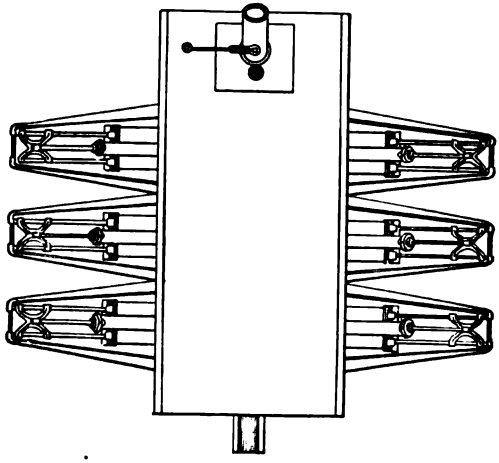


FIG. 46.

stead of at the top, as in his shaft-like furnace, was intended for both the reduction of iron ores to pig iron, and the refining of

pig iron to steel. As the figure shows, the furnace was meant to have three pairs of electrodes, which could all be used at once, or singly, for striking the arc, so that the temperature of the furnace could be regulated.

But even with this suggestion for a pure arc furnace Stassano

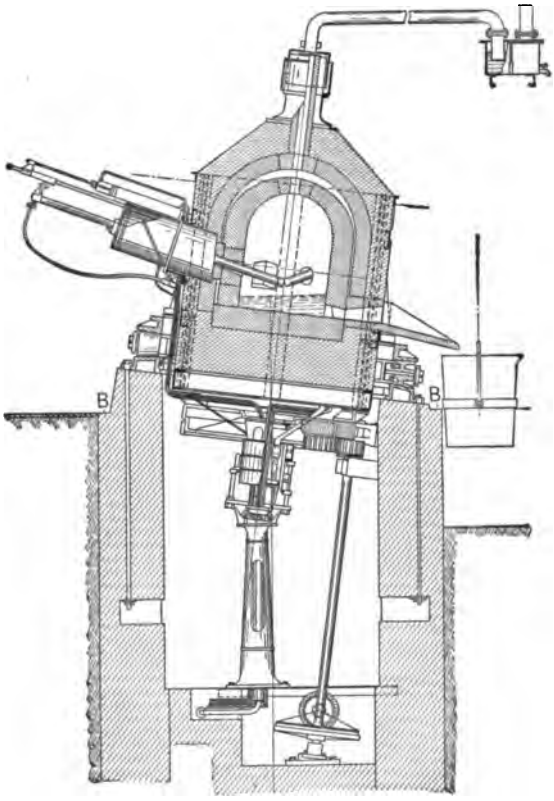



FIG. 47.

could not achieve success. He was however able to make a new furnace installation at Turin, Italy, in which he first used a rotating furnace. This furnace was patented in all industrial countries, and dated about the year 1902. As this furnace is in use to some extent today, it will be discussed in detail, showing as it does the best known furnace with purely arc heating.

Figs. 47 and 48 show the furnace in vertical and horizontal cross-section. It is very evident from the claim of Stassano's patent that he laid particular stress on the motion of the molten metal in the furnace.

As the drawings show (Figs. 47 and 48), the rotary arrangement of the furnace necessitates a vertical cylinder. The shell of the furnace is constructed of sheet iron, and is connected at the lower part, near the bottom, with a strong ring-shaped carrier,

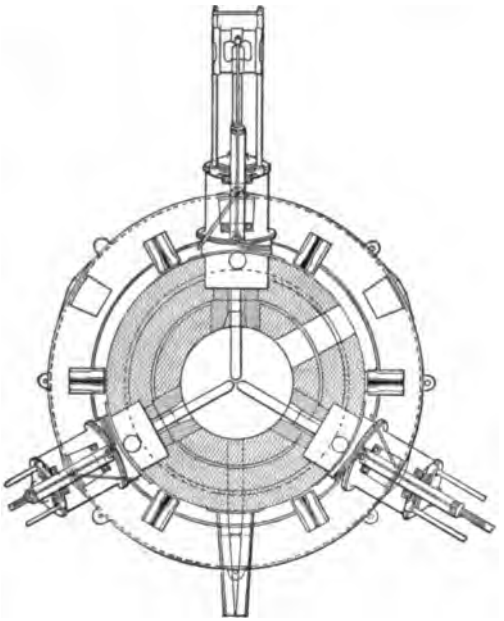


FIG. 48.

which in turn rests on rollers. The motion is usually transmitted by gears driven by an electric motor. At the middle of the furnace bottom, axial to the direction of the furnace, we find the current and water supply. The current is brought in by means of brushes and slip rings, such as are found on any polyphase motor. The water cooling, which is brought from the fixed to the movable part by suitable means, is needed for two purposes with this furnace. First, it serves as cooling water for the electrodes, and again as the water under pressure for the

electrode regulation. The figures show that the furnace hearth is covered with a double sort of roof, which is not readily removable with this type of furnace. This arrangement allows the heat protecting qualities of the brickwork to be utilized to a great extent, and, as a matter of fact, this method is said to give an extraordinary heat insulation, which can even be bettered by inserting layers of lime or sand.

Fig. 47 shows an outlet in the upper part of the melting chamber, allowing a free escape of the gases which are generated during the reaction. This outlet pipe is surrounded with a sand filled covering, into which it dips at its lower end. This pipe does not take part in rotation of the furnace, but is kept in place by suitable means.

The gas removing system again betrays the ambition of Stassano to smelt ore, and serves to protect the furnace completely from the entrance of outside air. As a matter of fact, however, this furnace did not give satisfactory results for smelting ores directly. On this account this furnace is today used only for the working up of scrap or for refining hot charges.

In such cases, therefore, this gas flue falls away, as in the installation of duplicate Stassano furnaces at the Bonner Maschinenfabrik, Bonn, Germany. The hearth here has also been given a hexagonal shape, whereas Fig. 48 still shows the round form as used by Stassano.

The bottom of the furnace consists of Magnesite brick,[1] as does also the double form of furnace roof. The insulating layers of furnace refractories are partly comprised of tamped in material. The furnace is provided with a door for watching the metallurgical work, for charging the metal, adding the slagging materials and rabbling it off, for taking samples, etc. Besides this the furnace bottom is supplied with a tap, through which the finished material flows.

The most essential and most important furnace part is, of course, the *arrangement of the electrodes*. As the furnace may be built as well for single phase as for three phase, it would have

[1] According to *Stahl und Eisen*, page 1066, 1910, the side walls and bottom are said to have lately consisted of tamped in dolomite.

two or three electrodes, as the case may be. These pierce the furnace walls as is plainly shown in Figs. 47 and 48 and form an arc or arcs in the middle of the furnace which heat the bath.

Stassano laid great stress on the *design of bringing the electrodes* through the furnace. The electrodes enter the furnace by first piercing double walled cylindrical chambers. There is a circulation of water in the space surrounded by both walls, in order to keep the temperature of the outer electrode portion down. There is a regulating cylinder over each cooling cylinder, the former aiding the setting of the electrodes to any desired point. The piston-rod is connected at its outer end by means of a sliding guide rod with the one end of another rod, which carries the electrode itself at the other end, which latter end is in the cooling cylinder. In order to better show this arrange-

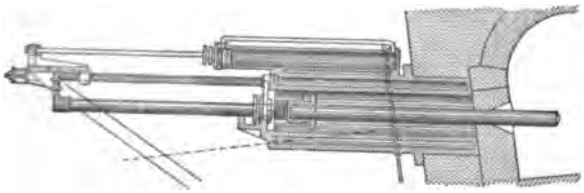


FIG. 49.

ment, the whole design of this electrode regulating apparatus is shown in Fig. 49 on a larger scale.

The regulating of the electrodes is accomplished without any automatic regulating apparatus, but is accomplished manually by the aid of the hydraulic cylinder. Any common water pressure of 4 or 5 atmospheres (60 or 75 lbs.) can be used, so that no special water pumps are needed for the electrode regulation. The current carrying parts are naturally easily and well insulated electrically from the furnace shell, as short circuits would otherwise occur through the furnace walls. Stassano did not look with favor upon any automatic regulating apparatus for his electrodes, and *Osann* who studied the operation of the Stassano furnace in detail gave the following reasons in a report in *Stahl und Eisen*, 1908: "An automatic regulating

arrangement would be complicated in any event and would not be advisable if for no other reason than this alone because the electrodes are withdrawn while charging; besides this, an electrode breaking off now and then is not precluded, and this fragment must be removed quickly. This is simply and quickly accomplished by calling to the man who watches the three ammeters, and operates the three corresponding levers which control the hydraulic cylinders for the electrodes. The electrodes can be used up until the remaining stump only protrudes .1 *m.* (4 inches). Then they are changed, and this change takes only from 3 to 5 minutes, all of which, I have personally assured myself."

We now come to the behavior of the furnace during its operation. As already mentioned, the electrodes are withdrawn when the furnace is being charged. When the furnace is about two-thirds charged, the electrodes are brought together, to again form arcs and are then regulated by watching the needles of the ammeters. The charging of the furnace with scrap takes about 15 minutes for a 1-ton furnace, and the setting of the electrodes thereafter, takes about two minutes. As soon as the first scrap is melted down, the remainder is charged on top of it, but this time without withdrawing the electrodes, *i.e.*, without any interruption of the current taking place and working with the utmost speed, so as to avoid all radiating losses. The slag-forming materials are charged in the usual way, and the dephosphorizing slag is likewise removed after the dephosphorizing period is over, similarly to the practise with any other electric furnace. In order to easily remove the slag, the furnace is turned far enough, so that it may be conveniently removed through the door. This is possible as the furnace axis has a definite angle of about 7° from the vertical, so that the door assumes different positions toward the bath surface, during the turning.

If after this general characterization of the Stassano furnace, we turn to one of its definite examples, we find that the duplicate furnaces at Bonn of 1-ton size are the best, being one of the later Stassano furnace installations.

These 1-ton furnaces of 250-HP are built for three-phase

current; 110 volts is needed to operate them. The current is supplied from a distant central station at an incoming voltage of 5200. This voltage can, of course, not be used directly in the Stassano furnace, and is consequently transformed in a separate transformer, removed from the furnace, and stepped down to the aforesaid 110 volts. During the normal operating condition, the furnace takes from 1000 to 1100 amperes at 105 to 110 volts, and this current is held as steady as possible throughout the entire operation. The Stassano furnace having a very good power factor, (as high as .9 to .95 per cent.,) the energy consumption for this 1-ton three-phase furnace is $1.73 \times 1100 \times 110 \times .95 = 198.86$ Kw., or say, 200 Kw.

It is necessary to have a man watch the electrical conditions. He regulates the arcing distances of the electrodes, by means of the levers controlling the hydraulic cylinders, and watches the ammeters, one of which is in each phase. The rotating motion of this Stassano furnace in Bonn is transmitted by means of a 5-HP motor to a tight and loose pulley, connected by a shaft to gears, one of which is a part of the furnace. The electrode diameters of all Stassano furnaces are kept down as much as possible, so that the work is carried on with comparatively high current densities. In furnaces up to 500 HP, electrode diameters of 80 mm. (3.2 inches) are used. According to an article by *Coussergues* in the *Revue de Metallurgie*, this diameter is also used in larger furnaces up to 1000 HP. In this case, however, the electrodes are doubled in number.

Accordingly, for the 250-HP furnace at Bonn, for instance, which takes 1100 amperes with its 80 mm. (3.2 in.) diameter electrodes, whose cross-section is 5024 square mm. (7.78 sq. in.) corresponding to

$$\frac{1100}{5024} = .22 \text{ amperes per square millimetre} \left(\frac{1100}{7.78} = 141 \text{ amps. per sq. in.}\right)$$

or 22 amperes per square centimetre.

With a 500-HP furnace having the same electrode cross-section and about twice the current, the current density would rise to

$\frac{2200}{5024}$ = .44 ampere per square millimetre $\left(\frac{2200}{7.78} = \begin{matrix}282.\text{ amps.}\\ \text{per sq. in.}\end{matrix}\right)$
or 44 amperes per square centimetre.

This, therefore, gives current densities which still substantially exceed those given by *Hansen*, as mentioned on page 91, even though these values had to be designated as being high enough. We have also then with Stassano furnaces to figure with a substantial heat generation in the electrodes. A short example may show this.

New electrodes for a 250-HP furnace have a length of 1.5 metres (59 inches). As the electrodes wear off during the operation, we may figure with an average length of 1 metre, ($39\frac{3}{8}$ inches). If we insert besides this the operating value for the resistance of carbon per cubic centimetre, as given by *Hansen* and shown on page 76 to be,

$$\rho_1 = .00183 \text{ ohms per cubic centimetre.}$$

we obtain the resistance of the electrode as being:

$r = \rho_1 \frac{l}{q}$ where $l$ and $q$ are in centimetres and square centimetres respectively.

Consequently:

$$r = .00183 \frac{100}{50.24} = .0036 \text{ ohm.}$$

The drop in voltage in the electrode of a 250-HP furnace hence is

$$e = ir$$
$$= 1100 \times .0036 = 3.96 \text{ say } 4 \text{ volts.}$$

The energy transformed into heat per electrode is consequently

$$A = ie \text{ watts} = 1100 \times 4 = 4400 \text{ watts,}$$

or in all $3 \times 4400 = 13200$ watts. That is, with a total energy absorption of 200 kw. for the furnace, there is 6.5 per cent. lost through Joule losses ($i^2 r$) in the electrodes alone.

Besides the transformation of electrical energy into heat in the electrodes as just described, several interesting phenomena will be found in the Stassano furnace as shown below.

First regarding the length of the arc, with Stassano furnaces with voltages of 110 up to a maximum of 150 volts, this distance

at first is about 10 cm. (4 inches) from electrode to electrode. During the run, however, the arc distance increases up to a length of 30 cm. (about 12 inches). This considerable lengthening of the arc is partly accounted for on the one hand by the high temperature of the furnace atmosphere, and on the other hand through the gasification of the electrode ends caused by the arcs between them. It is to be noticed that the arc sags toward the bath. This phenomenon can only be regarded as favorable to the heating of the metal bath.

We, therefore, find with the Stassano furnace, an increasing lengthening of the arc, as the temperature of the furnace atmosphere increases. The risk must, therefore, be run of having the arc break and making it anew, when charging the furnace with cold material which cuts the arc. On this account, therefore, particular care should be exercised when charging the furnace, entirely independent of the horizontal arrangement of the electrode rods.

If, notwithstanding this care, the arc should still break, then the rise of the furnace temperature is interrupted until the arc is again established. Still there would be no complete interruption of the energy absorption. Thus, according to Coussergues, when visiting the Stassano furnace at Bonn, the arc was interrupted, yet 300 amperes per phase at 120 volts were still taken up by the furnace, which is about one-third of the total energy.

This energy absorption with an interrupted arc is only then possible, if the refractories are heated to redness. For the energy absorption is dependent upon small arcs establishing themselves between the refractories and the electrode, which carry the current from the electrode to the magnesite bricks, after the latter have become conductors of the second class, due to the high temperature, and may therefore be regarded as heating resistances between the electrodes (see page 17).

Finally attention may be drawn to the capability of Stassano furnaces to be heated up electrically, since the charge is completely independent of the arc formation. In this way the furnace is also kept up to temperature during any shut-downs. This is accomplished by heating up for a quarter of an hour with

the arc, followed by a current interruption for three-quarters of an hour.

The above states the specific characteristics of the Stassano furnace. We now come to the *comparison* of the Stassano furnace with the ideal electric furnace, for which the requirements were laid down in Chapter V. Without entering into a discussion of the purely metallurgical questions which are gone into in detail in Part II of this book, we may say the following:

The first requirement stipulated that the electric furnace was to be capable of being operated *with any prevailing alternating current* at any voltage and periodicity.

This requirement is met by the Stassano furnace better than by any other of the well-known arc furnaces, for Stassano furnaces are built for single-phase as well as for three-phase current. At the same time any prevailing periodicity may be used. Opposite this, the necessity of transforming the voltage to that required by the furnace, only plays a secondary part, for this transforming takes place in comparatively inexpensive stationary transformers, which hardly call forth any particular vigilance, considering their great operating safety.

The second requirement, *viz.: the avoidance of sudden power fluctuations* is better filled by the Stassano furnace than by any other furnace, especially when melting down cold stock. For aside from the interruptions during the charging period, as already mentioned, the sustaining of the arc is in no way influenced by the melting process, so that if the attendant regulating the electrodes is sufficiently attentive, sudden current fluctuations should be reduced to a minimum. These conditions permit Stassano furnaces to be connected directly to the line without the interposition of costly regulating apparatus.

We now come to the third point in which an *easy regulation* of the current is demanded. This requirement may also be regarded as being fulfilled, as voltage regulation, simultaneously causes a regulation of the energy supplied to the furnace, which is entirely independent of such energy regulation which is provided by different settings of the electrodes. It was mentioned on page 111 that Stassano avoided every automatic regulation of

the electrodes with his furnaces, which would still offer several advantages. These reasons are referred to again at this time.

The requirement under 4, *viz.:* a *high electrical efficiency*, does not seem to be so completely fulfilled. We have already seen that the high current densities in the electrodes lead to important heat losses, and it does not seem therefore that it is possible to avoid considerable losses. This is even accentuated by the intensive water cooling of the electrodes. Unfortunately, figures regarding these actual losses are nowhere to be found, still they cannot be unimportant, as the example on page 114 indicates. Besides the electrode and cooling losses there are the transformer losses, for changing the voltage to the desired amount, for which about 3 per cent. of the total energy may be allowed.

The fifth point, *viz.:* the *tilting arrangement*, which Stassano replaced with a turning one, no doubt gives his furnace certain advantages; still, compared to the tilting device, his solution can hardly be regarded as a particularly happy one. The turning or rotating structure requires a really complicated mechanism. As a proof of this it is only necessary to refer to the water supply for the electrode regulation and to the electrode cooling. Entirely aside from this, it hardly seems advantageous to have a tapping hole, instead of pouring over the lip, when teeming, especially when heats follow each other quickly, as is usually the case when treating hot metal.

Even though the requirement of an *easily surveyed hearth* seems to be completely fulfilled, it is yet to be observed, that the almost horizontal arrangement of the electrodes makes the fulfilment of the seventh requirement so much harder. For the breakable electrodes with their comparatively small cross-sections are liable to crack off when roughly handled, so that the metallurgical operations in the furnace entail great attention and not a little dexterity. Besides this, the Stassano furnace would have the advantage of influencing the charge the least with its arc heating, in case electrode breakages could be avoided with certainty, as the carbon vapor from the electrodes is not directly against the molten metal. Relative to the *avoidance*

*of every under or over heating* of the metal, it must be said that the influence of the arc heating as employed by Stassano, *i.e.*, by use of the radiation, is the mildest way in which arc heating can be used at all, as the direct influence of a heating agency of 3500° C., on the metal, is avoided.

Without discussing the purely metallurgical demands, the fulfilment or non-fulfilment of which can be readily seen by the construction of the furnace, we find that the requirement of a *sufficient but not too strong a circulation of the bath* is fulfilled by the rotary arrangement of the furnace. No other mechanical circulation appears in the Stassano furnace as it is built today, and it seems, therefore, that if any security is desired for a complete uniformity of the material in its several layers, it is not possible to dispense with the mechanical bath circulation. And these necessary mechanisms must always be designated as being very complicated (for any such metallurgical apparatus as this), no matter how ingeniously the design may have been carried out.

Besides the many sided applications of this furnace, it would seem desirable if they could be built of any possible size. The proof of this is, however, yet to be established. For even though Stassano furnaces of 5-ton size were operated by Stassano himself, at the plant in his charge in Turin, the plant unfortunately has been temporarily shut down. It may, therefore, at present only be regarded as proven that the Stassano furnace of 600 to 1000 Kg. (5/8 to 1 ton), as it is operated at Bonn for melting up scrap for steel castings, succeeded in giving good results. The furnace does not seem suitable for larger sizes, as the sensitive devices permissible, at any rate, with small furnaces, while easy to watch, are hardly applicable with large furnaces. The high current density, with which 5-ton furnaces are to be operated, also seems unadaptable, while with still larger furnaces where the doubling of the electrode number would be encountered, difficulties could be expected from the simultaneous manual regulation of six electrodes.

Larger furnaces would have longer and consequently more breakable electrodes, which would otherwise need much room during the furnace's rotation. Finally, the easy working of the

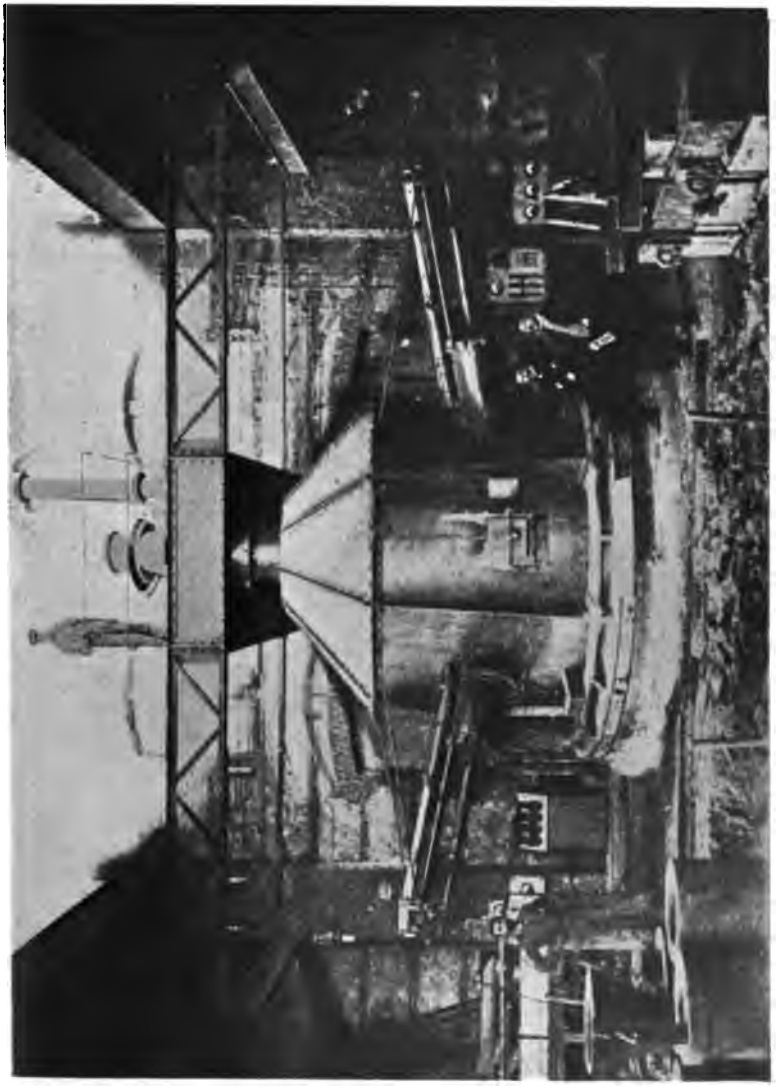


FIG. 50.

furnace becomes almost impossible with the six horizontal electrodes over-topping the bath. All these reasons make it appear that the Stassano furnace in its present customary form is only useful for small capacities.

The requirement of a *good thermal efficiency* is acceptably fulfilled. For even though the Stassano is the electric furnace where the metal is heated most indirectly, but where the atmosphere directly above the bath is heated the strongest, and though it is not possible to avoid a considerable heat loss when the furnace door is opened, still it is well to note that the heat insulation with the Stassano furnace is extraordinarily well carried out, and that consequently it is possible to attain satisfactory power consumption figures for melting a ton of steel. And these vary between 800 and 1000 Kw. hours per ton of steel for melting cold stock for making steel castings.

According to Osann (*Stahl und Eisen*, 1908, p. 660), we find that he begins with a cost of 62 cents for electrodes at the Bonn furnace and $2.75 for refractories per ton of steel, so that we cannot speak here of exactly low refractory costs, which could, however, be considerably reduced by using dolomite bottoms and side walls (*Stahl u. Eisen*, 1910, p. 1060).

The installation costs for a 1-ton furnace are given by Osann, inclusive of switchboard and foundation, at $8,750. This does not, however, say that the cost of the necessary transformer is included in this price. In Bonn the voltage is stepped down from 5200 to 110 volts. On the other hand, it may be said that at Bonn they were enabled to connect to an existing central station, so that in case such connection is not possible, the installation cost would be increased by an amount equal to the cost of an isolated plant (250 HP for a 1-ton furnace).

Fig. 50 shows a Stassano furnace from which the general arrangement is evident. Regarding the sale which these furnaces have had, reference is given to the list in Chapter XV. The giving of licenses for Stassano furnaces is made by the *Bonner Maschinenfabrik und Eisengieszerei* Fr. Mönkemöller & Co., Bonn on the Rhein, Germany.

# CHAPTER VIII

## THE HÉROULT FURNACE

HÉROULT had already earned great merit in the development of electro-metallurgy, on account of his electric furnace for the production of aluminum. He was the first to discover how to build an arc furnace for refining iron, having vertical electrodes pointing directly at the bath. Before this these furnaces had the objection, that the iron bath greedily absorbed the carbon from the immersed electrodes. On July 4, 1900, Héroult made the suggestion (see German patent No. 139904), that to avoid the absorption of carbon by the metal bath, the slag used to refine the metal should be inserted between the bath and the electrode.

According to the patent description the electrodes are to be so far separated from each other and are to dip so little into the slag, that, on the one hand, the resistance between the electrodes within the layer of slag, shall be great enough to force the current from the one electrode through the slag lying directly beneath it to the metal, and from the metal again through the same layer of slag to the other electrode, and that there shall be otherwise no connection between either electrode, and the metal. Further, according to the patent description, the striking of arcs between the electrodes and the metal bath into which the electrodes project, is not precluded, or is it necessary. Regulating the distance between the electrodes and the metal bath, however, is the important part. This must be accomplished in such a way that the slag layer between the electrodes and the metal bath remains hotter and more conductive during the entire refining period, than the layer of slag between the electrodes, because only in this way will the current take the path as prescribed above.

After this general characterization of the Héroult furnace, and before entering into details regarding its construction and

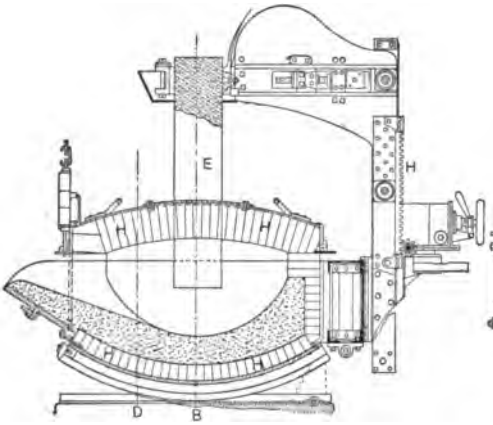



FIG. 51.

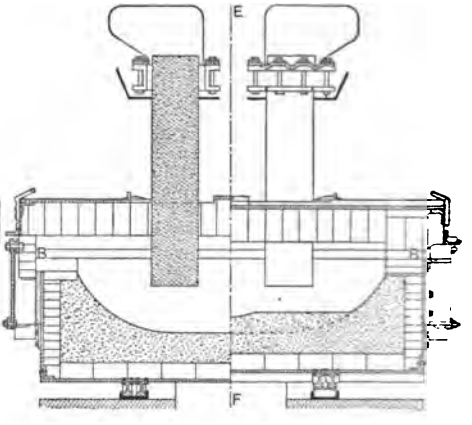



FIG. 52.

operation, we will give a short survey of the development of this furnace.

According to the *Electrochemical and Metallurgical Industry*, 1909, p. 261, Héroult, in his first efforts in building an electric

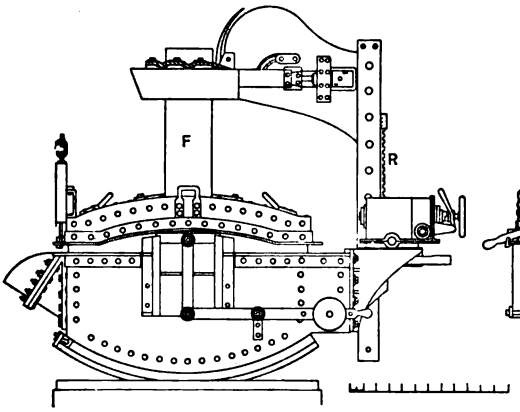



FIG. 53.

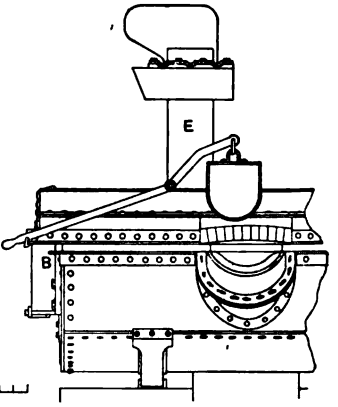



FIG. 54.

furnace, leaned narrowly toward his type of aluminum furnace. In this furnace, as is well known, one pole consists of a hanging

carbon electrode, while the other pole was made by the furnace hearth itself. For this purpose the hearth was made of carbon. When it was necessary, however, to obtain a material with the lowest possible carbon content, this style of furnace could no longer be used, as the carbon of the hearth bottom was greedily absorbed by the molten metal.

On that account Héroult next made tests with a furnace for the production of low carbon ferro chromium. The bottom of this furnace consisted of chromite bricks in the middle of which a carbon block was inserted which then acted as the bottom electrode. With this method Héroult hoped that a part of the

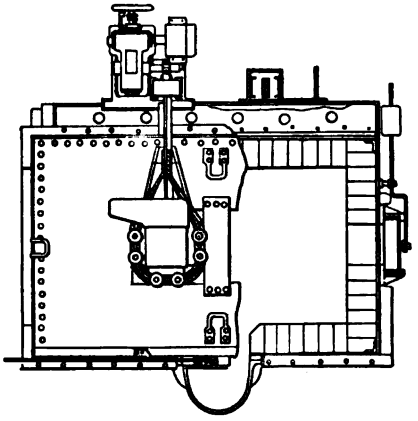


FIG. 55.

carbon block would be absorbed by the molten metal and that the molten mass would continue to force its way down absorbing carbon as it went, until the exterior radiation of the molten metal would cause it to freeze on the carbon block. Héroult hoped to keep this condition constant, so that there would be an interposition of the frozen metal between the bottom carbon electrode and the bath, which would at the same time prevent any carbon absorption by the bath.

But the tests as carried out did not fulfil his hopes, and so after further trials there was produced the Héroult furnace as we know it today. This has been characteristically shown by

the above examples, taken as they are, first of all, from the patent records. Furnaces of this kind were first put in trial in *Froges* and *La Praz*, France.

The first Héroult furnace in Germany was installed by the firm of Richard Lindenberg of Remscheid in 1905, and put in operation in February, 1906. Since then the furnace has come into extensive use, thanks to its simple design, and thanks to a thorough knowledge of the metallurgical operations, which have been thoroughly investigated at Remscheid.

Coming now to the furnace itself, we may say the following: Of all the arc furnaces the Héroult furnace resembles most nearly a tilting open hearth furnace. It consists of a steel plate shell of nearly rectangular form which has a rounded bottom. Fastened on to this are curved tracks, which permit the furnace to run in channels. The furnace is tilted by means of a hydraulic cylinder. The whole design of the furnace may be seen by consulting the Figs. 51 to 55 inclusive.

The lining of the furnace consists of fire-bricks *H*, which are laid directly against the steel plate shell, and on which dolomite is tamped. The roof is removable. It therefore consists of a wrought iron frame, lined with fire-brick *H*, the former also having convenient screw eyes so that the whole may be transported readily. The hearth may be easily inspected and the furnace may be easily operated during the charging period, as the furnace has three doors, one in the middle in front and one at each side.

The arched roof of the furnace is pierced by two or three electrodes. Copper cooling chambers are placed at the piercing points (not shown in the illustrations), which keep the carbon electrodes outside of the furnace at permissible temperature limits (as discussed in Chapter VI), and simultaneously cool the brick work at these points. Each electrode hangs from a right-angled support *R*, which is movable in a vertical direction at the furnace. This support, therefore, carries a rack, which is moved by a motor-driven pinion. The use of these small motors in this design permits a mechanical regulation of the electrode positions. In Remscheid these small regulating motors are of the single

phase 100-volt type. These motors operate automatically or by hand, according to whether a higher or a lower position of the electrodes is called for. Naturally the electrode clamps are insulated in an improved manner from the furnace casing.

Regarding the development of the automatic regulating apparatus of the Thury regulator, this was described at length in Chapter VI, pages 102–104. The electro-magnetic scales mentioned there are connected as a voltmeter to the Héroult furnace, as shown in Fig. 56 by the dotted lines. The voltmeter is designated by *m* in whose place we can imagine the electro-magnetic scales. Two scales are provided as each electrode is regulated separately. The scales are influenced by the voltage which lies

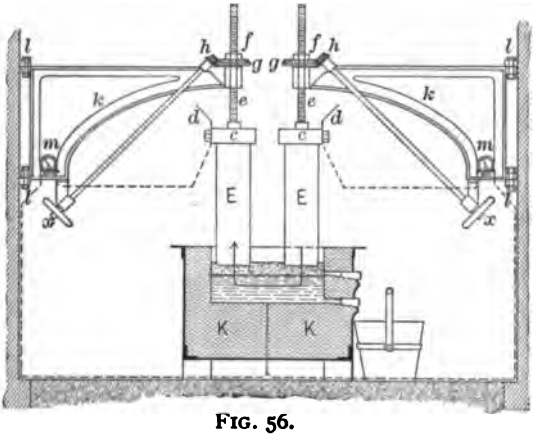



FIG. 56.

between the head of the electrode and the bath, which receives the main current. In order to obtain this voltage an iron rod is embedded in the furnace bottom, which in turn is connected to the remaining terminals of the magnetic scales. These scales are set so that a difference of two volts from the normal will start the regulator and keep it as near constant as possible.

The design of the furnace is such that either hot or cold charges may be treated. With cold charges, however, very heavy fluctuations of the current cannot be avoided, until the whole charge is melted down. The reason being that it is much harder to melt down a stone cold charge in an arc furnace and

maintain the arc, than it is to treat hot material. This is because an arc furnace always operates better at a high temperature, under the influence of which carbon evaporates. Furthermore, the appearance associated with the so-called over regulation causes the electrodes to become unruly, when, for instance, the heavy current fluctuations occur by the arc rupturing and establishing itself again. During the melting of a cold charge, continuous fluctuations therefore follow, and these continue until the charge has become molten. During the time of these heavy current fluctuations, that is while melting the metal, the automatic regulation is replaced by hand regulation with the Héroult furnace also. But the series connection of the carbon

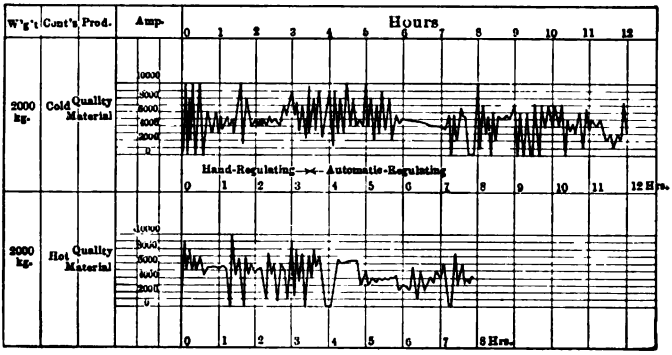



FIG. 57.

electrodes has a negative influence on the electrical conditions even with perfectly fluid metal. To illustrate this, Fig. 57 shows several current curves, as they were recorded by an arc furnace with series connected electrodes. These curves are reproduced from an article by *Englehardt* in the *Zeitschrift des Österreicheschen Ingenieur- und Architekten-Vereins*, during 1909.

In order that no misunderstanding may arise regarding the heating method of the Héroult furnace, it is well to especially mention at this time, that Héroult had soon to realize that he must employ an arc to make his furnace operate even though it deviated from the furnace operation of his patent description.

In this it was not precluded nor was it necessary that arcs should be struck between the electrode and the bath. Hence to-day the furnace voltages are chosen so high, that the electrodes are set at about 45 cm. (18 in.), above the steel bath. With this setting it is possible to obviate a carburization of the bath when the slag is interposed, and this is solely caused by the heating action of the arc, (having a length as mentioned above,) heating the metal to the desired temperature.

If the electrodes in the Héroult furnace were dipped into the slag, so that no arc exists, then the furnace would be of the pure resistance variety. Should we now calculate the resistance conditions in such a circuit, we shall immediately find, that, under these conditions, practically the whole energy would be changed into heat in the electrodes, without heating the bath materially at all. This is apparent when we compare the resistances of the two carbon or graphite electrodes connected in series, with their comparatively small cross-section and very great length and their high specific resistance, with the resistance of the slag layer and the bath with their very large cross-sections and very short lengths and the very low specific resistances (at least as far as the bath is concerned). These conditions have been clearly recognized by the representatives of the Héroult furnaces. We quote from Prof. Eichhoff of Charlottenburg, the technical adviser of Lichtenberg of Remscheid, his article appearing in *Stahl und Eisen*, 1909, p. 843, as follows:

"It is impossible to heat an arc furnace for steel, by utilizing the heat generated by the resistance of the thin slag layer or the large cross-section of the bath. These resistances only furnish a few per cent. of the heat necessary in the furnace," and again,

"Obtaining heat by the rising temperature of the slag with its decreasing resistance, or by utilizing the resistance of the bath, has never been achieved, simply because the slag layer is too thin, and the cross-section of the steel bath too large. Such a view therefore is a fable, which I oppose from the start."

This description should suffice to give a perfectly clear picture of the workings of a Héroult furnace, in which then practically the entire heating is obtained from the heat of the arc.

If we return for the moment to the furnace design we observe the following:

Héroult furnaces are usually built for single phase currents of from 25 to 33 cycles. The Héroult furnace, for instance, at La Praz operates on 33 cycle current at 110 volts. The charge is about 2½ tons. At this rate the furnace consumes about 4000 amperes. With very large furnaces[1] Héroult uses 3 phase instead of single phase current. This is done in his 15-ton furnace. One of these is operating at the works of the Illinois Steel Co., South Chicago, and another at the American Steel & Wire Co., Worcester, Mass. The hearth of this furnace is circular, over which the three electrodes are arranged at the corners of an equilateral triangle. The furnace is operated by three phase, 25 cycle current, delta connection, at 100 volts. Under these conditions, the current, per phase, rises to 12,000 amperes. As in other furnaces the electrodes are automatically regulated. The current is taken from a high tension circuit and stepped down by means of three 750 kw transformers to the desired voltage of 100. Accordingly the furnace for 15 tons takes—

$12000 \times 100 \times 1.73 = 2076$ kva, and as the power factor is between .8 and .9, it consumes actually—

$$2076 \times .85 = 1760, \text{ say } 1800 \text{ kw.}$$

The difficulty of building one of these large arc furnaces lies in the increasing difficulty of finding a suitable electrode design, which will be durable in service and not have too great electrical or thermal losses, at the same time not injuring the general view of the hearth too much. This feature will be alluded to later on.

In order to give an idea of the dimensions of the electrodes in Héroult furnaces, it may be well to mention that the electrodes carrying 4000 amperes in the single phase furnace operating at La Praz have a cross-section of $360 \times 360$ mm. = 129,600 sq. mm. ($14.1 \times 14.1$ inches = 200 sq. in.), and a length of 1.70

[1] In 1912, the *Metallurgical and Chemical Engineering* reports that a 25-ton Héroult furnace was put in operation at the Gewerkschaft "Deutscher Kaiser," Bruckhausen, Germany.

metres (67 inches). They consequently operate at a current density of

$$\frac{129{,}600}{4000} = 32.4 \text{ sq. mm. per amp.} \left(\frac{200}{4000} = .05 \text{ sq. in. per amp.}\right.$$

$$\text{or } \frac{4000}{200} = 20 \text{ amps. per sq. in.}\Big)$$

If we take into account that as the height of the furnace roof over the bath is 70 cm. (27½ inches), and the clamping length at the top of the electrode is 35 cm. (13¾ inches), we find that there is a certain length of usable electrode, which with a total length of 1.75 metres (69 inches), makes the usable portion about 70 cm. (27½ inches). The *un*usable portion of the electrode is consequently about 1 metre (39 inches).

If we now calculate the electrode voltage losses in accordance with the figures just mentioned, similar to the electrode losses determined for the Stassano furnace, we obtain the following:

Assume specific resistance of carbon in operative condition =

$$\rho_1 = .00183 \text{ ohms per cubic centimetre}$$

then as $e = i \times r$, where $r = \rho_1 \frac{l}{q}$, and $l$ and $q$ are respectively in centimetres and square centimetres, we obtain—

$$e = i \times \rho_1 \times \frac{l}{q} = 4000 \times .00183 \times \frac{100}{1296} = .565 \text{ volts.}$$

For both electrodes, then the drop is 1.13 volts, because they are connected in series.

The result as figured, however, cannot be considered as correct, because the change in the specific resistance with increasing cross-section was not taken into consideration. In the calculations, so far, we kept the probably correct value of .00183 ohm per cubic centimetre, which is in keeping for an electrode of 80 mm. diameter, whereas the electrode of the Héroult furnace in question corresponds to a square having 360 mm. to a side. If this had been taken into consideration, then the value of $\rho_1 = .014$, (when following the values given on pages 93–94), should have been chosen for the electrode condition in its cold state. Should, on the other hand, the values of Hansen be taken, where the

resistance falls to about 40% in operation, compared to the cold resistance, then the determination should have been figured with $\rho_1 = .0056$ ohm per cubic centimetre.

Figuring more correctly then with this value, we obtain,

$$e = 4000 \times .0056 \times \frac{100}{1296} = 1.73 \text{ volts per electrode.}$$

The drop for both electrodes is consequently—

$$2 \times 1.73 = 3.5 \text{ volts.}$$

This gives a loss three times as high as in the first calculation. This example clearly shows of what importance it is to accurately know the different constants for this material for the different cross-sections. For it is only with these that the determinations of the conditions arising in the electrodes can be figured.

Of course it is not to be supposed that this last value gives a final idea of the *total losses* in the electrodes, because in the calculations just made only the purely electrical losses were judged. This, too, with the rather hazardous assumption that the constant taken for the specific resistance of the carbon electrode is correct. Meanwhile, the radiation heat losses have been entirely disregarded. It is undoubted, that the latter raises the total electrode losses considerably, and even though determinations regarding radiation heat losses are hardly possible, still it may be said with some certainty, from measurements of other arc furnaces, that the total electrode losses generally, as well as in the Héroult furnace under discussion, will not be below 7 to 10%.

These losses do not only appear of this value in the comparatively small furnaces, such as have just been discussed, *i.e.*, of the 2- to 3-ton size, but especially in the larger sizes. With the size of the furnaces and the increasing cross-sections of the electrodes, the difficulty also grows of obtaining favorable material constants, which is a thing entirely apart from the difficulties to be surmounted of procuring large electrodes of considerable durability. Chapter VI brings out these details. It may be said further regarding the practical operation of the 15-ton, 3-phase furnace at South Chicago and Worcester, that it has not

been found possible to increase the proportions of the electrodes at will. As has been remarked this 15-ton furnace operates with about 12000 amperes per electrode. The conduction of such currents naturally necessitates very considerable electrode cross-sections. It was at first tried to produce these electrodes in single large blocks. According to the *Electrochemical and Metallurgical Engineering*, 1909, p. 262, one of these block electrodes had a diameter of 2 ft. (60.9 *cm.*), by a length of ten ft. (3.048 *m.*). The weight of one of these electrodes was about 3200 lbs. (1451.5 *Kg.*).

The results with these colossal electrodes was hardly satisfactory, as breaks often occurred which disturbed the operation of the charge in a most sensitive way, even though the current density operated with was 28 amperes per square inch, or 4.35 amperes per square centimetre, corresponding to 24 sq. mm. per amp., which is a comparatively high density in spite of the large electrode cross-section. (See Chap. VI, page 82.) On that account they sometimes use the dearer but less troublesome graphite electrodes instead of the carbon electrodes. Quoting from the *Metallurgical and Chemical Engineering*, 1910, p. 179, and following pages, we find that the electrodes as used are made up of Acheson graphite rods, 48 in. long (122 cm.), and 8 in. (20.32 cm.) in diameter. Three such rods are butt-connected to a total length of 144 in. (366 cm.), and three such 144 in. rods are arranged side by side to form a single electrode, consisting (see Fig. 60 a and b) thus of a solid bundle of three rods, each 144 in. (366 cm.) long. The cross-section is therefore $3 \times 50.2 = 150.7$ sq. in. ($3 \times 324 = 972$ sq. cm.). The consumption of these electrodes is given as averaging 6.6 lb. (3 kg.), per ton of steel, and this figure is stated to be true both for graphite and for amorphous carbon.

The unavoidable wearing away of the comparatively dear electrodes, naturally causes an increase in the steel conversion costs, which is hardly desired. In the beginning there were additional losses of considerable moment which had to be reckoned with. These were caused by the unusual lengths of the electrodes in the electrode clamps and the length necessary for the distance between the furnace roof and the slag layer. These

costs are said to have now been reduced to the irreducible minimum, by using the otherwise worthless stub ends for a new electrode. Figs. 58 and 59 show two possible ways in which the greatest use can be made of the electrodes.

Fig. 58 shows the electrode made from shorter pieces with staggered ends held together with graphite screws. This method is also reported to have been used with the 15-ton furnaces in the United States. Fig. 59 shows a threaded hole in the end of the electrode. On the one hand this scheme enables the conducting clamp to be made of cast copper, as the figure shows, whereas otherwise, should the whole electrode become too short, it can be unfastened at the copper casting, a graphite screw inserted in its place, and a new electrode piece screwed between the too short electrode and the new one. This is also evident from a view at Fig. 59. The latter way of lengthening the electrode is used at the Steel Works of Richard Lindenberg, at Remscheid, Germany. It seems from this that the possible difficulties due to the higher resistance at the points of contact are not so great as might be expected from theoretical calculations.

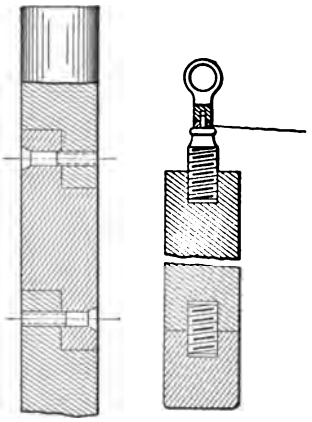


FIG. 58. FIG. 59.

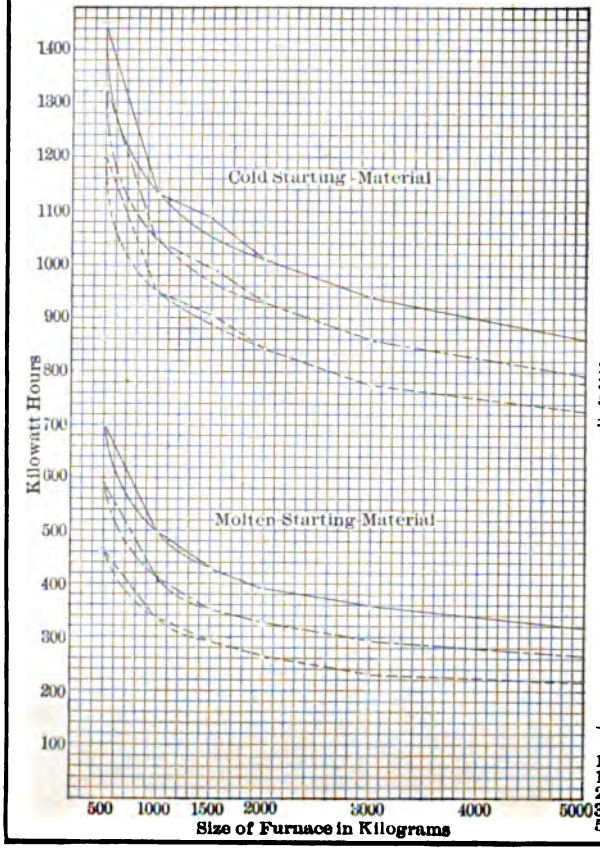
Following this it may be well to relate further details of the operation of the Héroult furnace. If the Héroult furnace is to be heated up after putting in a new lining, or owing to the operation being interrupted by Sunday, it is accomplished by charging the furnace with some coke, which acts as the heating medium and at the same time as the conductor from one electrode to the other, (as long as the heating of the furnace is accomplished electrically,) before the charging of the regular metal. After the furnace is charged the electrode regulation is performed manually, especially when scrap is to be melted down. This, however, often occurs when hot metal is first charged when

beginning operations. For instance, the 15-ton furnaces above mentioned are so regulated, whereas during the normal operation the regulation is also here accomplished by means of the Thury regulators.

As with all other electric furnaces, so also with the Héroult furnace, we find that the *power consumption* varies greatly with the size of the furnace, with the kind of charge used, and the desired quality of the finished material. A graphic picture of the change of the current consumption varying with the size of the furnace is given by Fig. 60. This data is given by *Eichhoff*. Here one set of curves represents the conditions for cold and one for hot charges. In the upper set of three curves the lowest one indicates conditions when only one slag is used, the middle curve when two slags are used, and the highest curve when three slags are used, and similarly for the lower set of three curves. In this way the curves show a rising degree of purity in the metal. The table accompanying Fig. 60 gives the quantities directly. Of particular interest are the operating figures which have been achieved with the 15-ton furnace. According to the report in the *Metallurgical and Chemical Engineering*, of 1910, p. 179, ff., the electric furnace is charged with hot metal from the Bessemer converter.

On the average here 12 charges are made daily, with an average time of 1 hr. and 15 minutes to 2 hrs. and 15 minutes, the weight of metal averaging from 12 to 14 tons. The average consumption of power for this is 200 KW. per ton of steel produced.

If we now pass on to the comparison between the Héroult furnace and the ideal furnace, we come to the first demand of an electric furnace, *that every existing alternating current can be used*. The Héroult furnace fulfils this demand only in part. As every arc furnace needs a certain voltage, the Héroult furnace also demands a specific potential, so that in nearly every instance a stationary transformer becomes a necessity, in which the high pressure of the distant central station is stepped down to the desired 100 to 110 volts at the furnace. The use of one of these transformers is almost unavoidable with any arc furnace. We saw further that up to the present the 15-ton Héroult furnace




| Tapping weight in metric tons | Size of Dynamo in Kilowatts | Average Kilowatts at Terminals. | 3 Slags Remv'd: KW. hrs. per ton / Average KW. (4) × Wght. | 3 Slags Remv'd: KW. hrs. used per ton of Steel | 2 Slags Remv'd: KW. hrs. per ton / Average KW. (5) × Wght. | 2 Slags Remv'd: KW. hrs. used per ton of Steel | 1 Slag Remv'd: KW. hrs. per ton / Average KW. (6) × Wght. | 1 Slag Remv'd: KW. hrs. used per ton of Steel |
|---|---|---|---|---|---|---|---|---|
| | COLD CHARGE (SCRAP) | | | | | | | |
| .5 | 250 | 200 | 3.63 | 1,450 | 3.32 | 1,330 | 3.00 | 1,200 |
| 1. | 310 | 250 | 4.55 | 1,135 | 4.17 | 1,040 | 3.78 | 945 |
| 1.5 | 375 | 300 | 5.43 | 1,086 | 4.98 | 996 | 4.53 | 906 |
| 2. | 440 | 350 | 5.78 | 1,010 | 5.30 | 928 | 4.82 | 844 |
| 3. | 550 | 440 | 6.40 | 940 | 5.85 | 859 | 5.30 | 778 |
| 5. | 750 | 600 | 7.22 | 868 | 6.63 | 795 | 6.05 | 725 |

| Tapping Weight in Metric Tons | Size of Dynamo in Kilowatts | Average Kilowatts at Terminals. | 2 Slags Remv'd: KW. hrs. per ton / Average KW. (10) × Wght. | 2 Slags Remv'd: KW. hrs. used per ton of Steel | 1 Slag Remv'd: Kw. hrs. per ton / Average KW. (11) × Wght. | 1 Slag Remv'd: KW. hrs. used per ton of Steel | Not Slgd. Off: KW. hrs. per ton / Average KW. (12) × Wght. | Not Slgd. Off: KW. hrs. used per ton of Steel |
|---|---|---|---|---|---|---|---|---|
| | HOT CHARGE (MILD FLUID IRON) | | | | | | | |
| .5 | 218 | 175 | 2.00 | 700 | 1.68 | 588 | 1.33 | 465 |
| 1. | 265 | 215 | 2.29 | 493 | 1.91 | 410 | 1.55 | 333 |
| 1.5 | 312 | 250 | 2.60 | 433 | 2.15 | 357 | 1.78 | 296 |
| 2. | 362 | 290 | 2.73 | 396 | 2.24 | 325 | 1.82 | 263 |
| 3. | 456 | 365 | 2.97 | 360 | 2.42 | 294 | 1.92 | 233 |
| 5. | 643 | 515 | 3.15 | 324 | 2.57 | 265 | 2.13 | 219 |

FIG. 60.

is operated with three phase current, whereas all his smaller furnaces are operated with single phase current. As it has proven possible to operate large furnaces with three phase current, it is obvious that the building of three-phase Héroult furnaces is constructively feasible. If, in spite of this, the building of such three phase furnaces has not taken place, the reason can only be sought in operating difficulties, be they electrical or metallurgical. Furthermore, with a new power plant nobody would decide to install the dearer single phase machines, if one could operate successfully with the cheaper three phase machines which are often already installed. It is not very hard to find the causes which have made it seem non-advantageous to use three phase current for normal Héroult furnaces of 2 to 5 tons capacity. The arrangement of three electrodes with their regulating mechanisms on furnaces of this size, makes the whole outside appearance of the furnace less simple and obstructs the general view, which is emphasized even more when considering the obstructed view of the comparatively small hearth. On the bath of these hearths three electrodes would appear which would hinder the metallurgical operations and lead to greater breakages of the electrodes, than two electrodes alone would, of which it is reported that breakages are rare during operating. In addition the arrangement of three electrodes would require the furnace roof to be pierced three times, which seems so much more dubious, as the arched roof is subject to the high temperatures of the arcs, and also to the water cooling around the three electrodes, so that inside of the comparatively small space of the furnace roof, we would have several large differences of temperature arising, which naturally tend to weaken and destroy the roof. Finally it must also be mentioned that three electrodes radiate more heat due to their larger surface than two electrodes do, having the same total cross-section.

These reasons show us, therefore, why 5-ton Héroult furnaces at present are only operated by single phase current. The consequence of this being that, when furnaces up to 5-ton capacity are to be installed where three phase current is available, a three phase single phase motor generator becomes necessary.

Whereas, if a new central station is to be built, it would be correspondingly dearer, as single phase generators are costlier than three phase generators. Larger furnaces which can be operated with three phase current consequently only require the installation of stationary transformers, provided the central station is large enough to stand the prevailing power fluctuations.

Up to the present time the avoidance of *sudden power fluctuations* has not been attained when operating Héroult furnaces. At present the Héroult furnace, with its electrodes in series, is credited with having the heaviest power fluctuations of the better known arc furnaces. This, as we have seen, is particularly so when melting down cold stock, during which time the fluctuations often become so great that the automatic regulation fails, and the hand regulation has to be resorted to. The conditions are more favorable as soon as the charge is completely melted, or when only treating hot charges. Once again, reference may be made to the curve shown by Fig. 57.

*Easy regulation* of the power is present in the Héroult furnace, the same as it is in every other electric furnace.

In judging the *electrical efficiency* of the furnace, the losses in the transformer are first to be taken into consideration, and then the losses in the carbon electrodes. In case any rotary transformers have to be used, the considerable losses appearing here have to be added.

In order to give a probable conception of the electrical losses the efficiency of the transformer may be taken as about 96 to 97%; the electrode losses at about 10%, of which at least 3 to 5% are purely heat losses, and in case rotating transformers have to be used the efficiency of these machines may be taken at about 85%.

The further requirements of a *tilting furnace*, and an easily surveyed and accessible hearth are fully met.

It has already been mentioned in which way Héroult knew how to avoid the undesired reducing action of the electrodes impinging directly on the metal. It is to be noted, however, that this reducing action cannot be altogether avoided, due to the electrodes throwing their carbon vapor stream against the

layer of slag, even though the slag layer protects the bath from this action. The prolonged carbonizing action of the arc furnace makes more difficult the oxidizing processes; for instance, during the removal of the phosphorus it cannot be without its influence on the time of treating the charge and the power consumption. When removing the slag it is well to consider that the carbonizing

FIG. 60*a*. — Héroult 3-phase furnace of 15 tons capacity. Teeming a charge.

action of the arc remains the same, even though the heating is not interrupted during this period.

If we now take up the requirement of the *motion of the charge*, we find that from reasoning alone, from the standpoint of purely thermal action, it is not present. For, as the arc operates only on the surface of the bath, the hottest parts of the bath are to be looked for here. On account of the electric current, on the other hand, a certain motion of the bath takes place, as this current

flows through the electrodes, and a part of the bath which is, to a certain extent, a moving conductor (as the motor action of the electric currents acts as discussed in Chapter III). For, in accordance with the conditions there given, the bath, or the part which is a movable conductor, is pushed to one side, so that the material beneath the electrode is under certain magnetic pressure, which causes a certain motion in the bath of the Héroult furnace. With all this, it is not correct to assume that the motion caused in the bath of the Héroult furnaces reaches the bottom of the bath.

The *application of the furnace* has a wide scope, although it is restricted from the melting of cold stock, due to too great fluctuations of the power, or if in other cases the installation of a rotary transformer is not considered prohibitive. However, it must not be left unsaid that at present the Héroult furnace is the only one which has been built for a charge of 15 tons, which proves the adaptability of the furnace for this size. Up to a certain point naturally the heat losses become proportionately smaller. However, it is to be feared that, for instance, with very large arc furnaces with three electrodes the furnace roof will have to be renewed quite often. The renewal of these new roofs for the usual 3 to 5 ton size furnaces is not exactly pleasant, to say nothing of the cost entailed. These renewals are, however, to be feared even more with the large furnaces with three openings in the roof, for besides the long span of the roof, there are the large differences of temperature between the various parts of the covering. This disadvantageous trait remains even though it is considered that the vertical electrodes act with a sort of umbrella action, and in so doing at least keep the most intense heat away from the roof. It is to be noted here that, for instance, the roof of the 15-ton furnace at the Illinois Steel Co., has to be changed every Sunday. According to the *Metallurgical and Chemical Engineering*, a roof such as this costs about $60. If a longer life is desired of the roofs of the Héroult furnaces, then it seems that the only course left is to make the covering as high as possible above the hearth. This would, however, cause larger electrical losses, as the current

would have to travel along a greater length of electrode, which would also cause greater heat losses, as these grow with the enlargement of the free space between the bath and its arched cover.

All these reflections seem to point to the 15-ton size as the largest Héroult furnace to be recommended at present. This

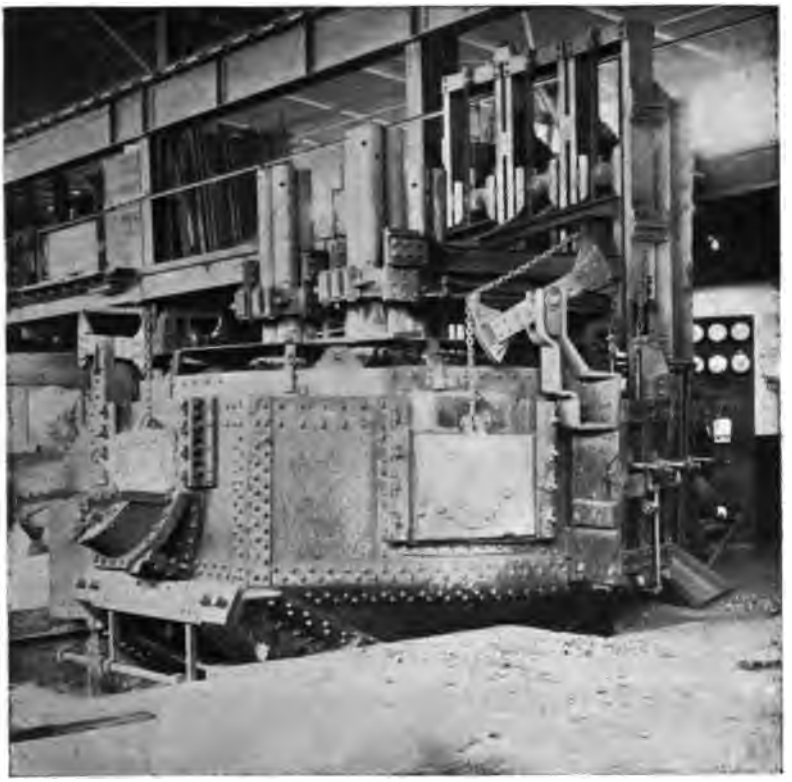


FIG. 60*b*. — Héroult 3-phase furnace of 15 tons capacity, at Worcester, Mass.

may be emphasized even more, considering the serious difficulties which have been encountered with the electrodes obtainable today for this size furnace. That these difficulties have not yet been overcome may be judged from the report appearing in the *Metallurgical and Chemical Engineering* for 1910, p. 179ff.,

where the electrode temperature, just where it issues from the furnace was measured and gave 1050° C. It is evident that these electrode temperatures cause a greater consumption of the electrodes, so that this may also be looked upon as part of the cause for the high consumption of 6.6 lb. (3 Kg.) of electrodes per ton of steel.

It is also to be noted that it must be possible to change the slag in an electric furnace, as is now done in the open hearth furnaces. The removal of this slag, however, becomes more difficult with the increase in the size of the furnaces, because the slag must be entirely removed. A mere running off of the slag is not sufficient, but a thorough rabbling off is necessary. In taking these conditions into consideration the *Electrochemical and Metallurgical Industry* of 1909, p. 262, says in referring to the attainable size of the Héroult furnace:

"As to the maximum size of furnace which it is now possible to construct, it is the intention to build them up to 30 tons. Very much will depend however on the work which has to be accomplished, that is to say, whether one or two slags would be used. In case of one slag, Mr. Turnbull is sure that a 30-ton furnace is possible, but should two slags be used, owing to the difficulties which might be encountered in raking off the first slag it may be found that a 15-ton capacity is nearing the limit. It could certainly be worked quicker than one of a 30-ton capacity."

Attention is again called here to the influence of the furnace size on the *thermal efficiency* of Héroult furnaces, and this point is dwelt upon more in detail. Prof. Eichhoff says the following in *Stahl und Eisen*, 1908, p. 844:

"I cannot think of a small furnace that has an efficiency of more than 50%. If the furnaces become larger and larger, then the actual useful absorption of the heat may rise to 70%, for the reason that the furnace surface does not increase in the same ratio as the furnace contents do. As the furnaces become larger the losses gradually decrease going from 50 to 40, and from 30 to 25%. I can tell you from my own practical experience, that comparing a 3-ton furnace to a 1.5-ton furnace, the effective current increase was only 10%. Hence, the current consump-

tion per ton of steel decreases materially. Owing to this fact we are compelled to build larger furnaces, and there is no reason why this cannot be done."

Since then there has been built the furnace of 15 tons, as mentioned by Eichhoff. For this size the above deductions are correct, however, with the limitations that the furnace efficiency cannot be further increased by further increasing the size of the furnace unit. The efficiency of furnaces of increasing sizes with two electrodes follows the curve of a parabola. However, where three electrodes are used, the efficiency will naturally decrease, due to the higher thermal losses, which latter gradually reach the practical attainable minimum, with the increasing size of furnaces. As Héroult furnaces, however, are built today, these losses will not be less than 25%.

It is difficult to calculate definite *Héroult furnace installation costs*, as these will in all cases be determined largely by local conditions. The direct connection of a single phase Héroult furnace, to an existing power plant, will hardly ever occur as the latter are usually of three phase design. Hence, the single phase furnaces necessitate a single phase, three phase rotary phase changer which is more expensive than the furnace itself. Comparing Héroult furnace installations with others, the former appear at their best when each installation has its own generator set. Besides this, as has already been pointed out, it is necessary to install a low tension regulating transformer near the furnace, which lowers the higher potential of the central power plant.

In giving the installation costs of some Héroult furnaces, we may figure roughly with the following values:

For a 5-ton Héroult furnace, a special single phase generator at 25 cycles of 600 KW. would be necessary, costing about $9,000, including foundations, erection and controlling switchboard. This, however, does not include the prime mover. To the above cost comes the furnace transformer, the transformer apparatus for regulating the electrodes, the cables and fittings, and the furnace itself with its regulating and tilting mechanisms. This will entail an additional cost of $12,000.

We would, therefore, have to reckon with $21,000 for a 5-ton Héroult furnace installation, including the generator, provided it is not desired to connect to existing three phase power mains. If, however, this becomes desirable for any reason, then a motor generator must needs be added, increasing the above prices by $6,000, so that in this case the total cost would be about $27,000.

In all the above calculations, the cost of buildings, etc., are omitted.

In closing, the advantages which Héroult himself gives of his furnace, over other arc furnaces, are here set down, especially those opposed to the Girod furnace, which latter is described in the following chapter. The advantages mentioned are taken from the *Electrochemical and Metallurgical Industry*, for 1909, p. 261:

"First—The total absence of electrical parts in the furnace proper, it being nothing else but a modified open hearth with the heat introduced above the metal by the electric current in place of gas. This in itself is an important factor as it does away with the bottom pole, considered by Héroult to be always the cause of much trouble in electric furnace work, and allows of any patching necessary to the bottom or side, without interfering with the work of the furnace.

"Second—The heat being introduced by means of two electrodes working in series, the current passing through the bath from one electrode to another and *vice versa*, necessitates carrying only one-half the current that would be the case should the current flow from one electrode through the bath and then through the bottom of the furnace, if the power is the same in both cases. Thus, all the conductors are reduced to one-half the section required in the other case and the electrodes can perform more efficient work owing to the lesser density of current to be carried."

The above-mentioned advantages of the Héroult furnace should be compared to the advantages of the Girod furnace, mentioned at the end of the following chapter. Furthermore, the opinion in the first paragraph may be supported. It is correct, of course, that certain advantages accrue by lessening

the cross-section of the current carrying conductors. He, however, avoids mentioning that these advantages are only attainable by raising the voltage. Even though a 110-volt alternating current pressure is usually harmless, yet sensitive persons are apt to experience most uncomfortable shocks. For this reason it is commendatory that the operators of a Héroult furnace protect themselves against these shocks, by, say, wearing wooden soled shoes which are insulators when dry. The opinion of Héroult that the series connection of the electrodes gives more useful work, is not substantiated in any way. We shall see later on that the total electrode cross-section of the Héroult furnace is not greater than with the Girod furnace, disregarding entirely how incomprehensible it is that Girod does not also operate with the same current density and the same low current densities as Héroult does. It still remains to be proved that operation with low current densities is an advantage, irrespective of the size of the furnace.

Relative to the use to which the Héroult furnace has been put, reference may be had to the statistics in the closing chapter. Licenses for Héroult furnaces may be obtained in Germany from the Elektrostahl, G. M. b. H., Remscheid, Hasten, and in the United States from the United States Steel Corporation, New York.

# CHAPTER IX

## THE GIROD FURNACE

THE Girod furnace, as well as the Héroult furnace, deserves the greatest consideration among arc furnaces. *Girod* originally made ferro alloys in a resistance furnace, in which the heat flow went through the walls, as described in Chapter III. It was in 1906 and 1907 that he turned quite experimentally to the melting of iron. He built a furnace with a capacity of about 1 to 1½ tons of a similar type to that used by Héroult, before the latter went over to his electric furnace with series connected electrodes. Where

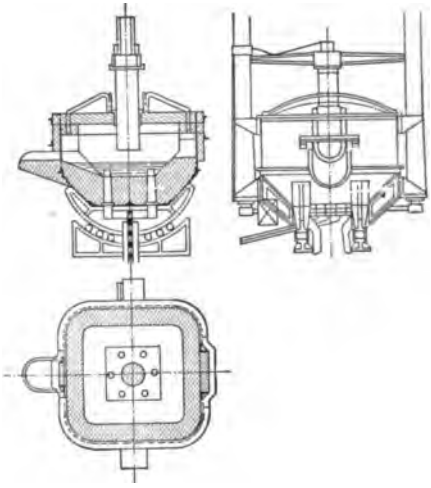


FIG. 61.

*Héroult* did not succeed in obtaining satisfactory results with his furnace, having one pole in the form of a hanging electrode, and the other pole as a bottom electrode, *Girod* succeeded. *Girod's* success has been so great in bringing this furnace to such a fully developed scientific reality, that it is hard to say at present to which of these two contestants, in the arc furnace field, the victory will finally belong.

In outward appearances the Girod furnace greatly resembles the Héroult furnace. The furnace casing is made of steel plate and either of the round or rectangular form. This in turn receives a lining of either dolomite or magnesite, making the bath either round or square shaped, as the case may be. The furnace roof is made of silica brick and is removable. The furnace itself is of the tilting variety. Because of this the first furnace at Ugine, France, was provided with trunnions at the side, which allowed the furnace to tilt in its bearings. In the newer design the furnace casing is furnished with a saddle resting in rollers,

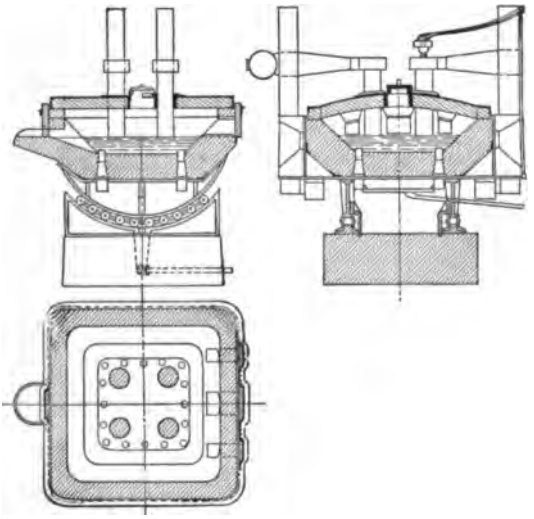


FIG. 62.

as shown in Figs. 61 and 62. The power for the tilting mechanism may be of any kind, but is usually an electric-motor. The Girod furnaces are supplied with two doors, one of which serves mainly for the charging and operating of the furnace, while the other is provided with a teeming spout, for the tapping of the furnace.

The most interesting part of the Girod furnace is, of course, the *arrangement of the electrodes* in which centres the whole principle of the furnace. Where in the Héroult furnace the

electrodes are of opposite polarity and arranged above the bath. Girod avoids this by placing one pole above and one beneath the bath. When the current strength increases with larger furnaces, and a duplication of the electrodes becomes necessary, then these are connected in parallel. This always permits electrodes of the same size to be used, and like poles are therefore either only above or below the molten metal. This arrangement, which naturally only allows the electrode above the bath to be of carbon, from which the current flows to the liquid steel in the form of an arc, allows the other pole lying beneath the bath to be of a special formation. In the Girod furnace this bottom electrode consists of a number of soft iron rods, which are arranged at the edges of the hearth, as seen in the horizontal cross-section of Figs. 61 and 62. In order to avoid these bottom electrodes from melting off too far, the parts protruding through the furnace bottom are water cooled. During the operation then a part of these electrodes melts away, after which pasty layers, followed by solid ones, issue toward the bottom of the electrode material, as soon as the cooling on one side is balanced by the heating on the other. The part of the electrode which is melted away is about 5 to 10 *cm.* (2 to 4 inches) long, whereas the space for the water-cooling at the lower end of the iron block is 150 mm. (6 inches) deep. This water cooling not only provides a nearly unlimited durability to the bottom electrodes, but it also materially aids the life of the bottom refractories. From data given by Borchers, the furnace bottom is said to last 120 to 160 heats when melting cold stock, before repairs are necessary. During this time the bottom wears away to the extent of 100 mm. (4 inches), whereas the walls of the furnace need repairing after only 80 heats.

It may also be mentioned here, that Girod endeavored to utilize air cooling in place of water cooling for the bottom electrode, but at present water cooling is again generally used.

What has been said of the Héroult furnace relative to the hanging carbon electrode also applies here. The adjustable electrodes are held in their supports, which are in turn fastened to the furnace. The regulation is automatic and the Thury

regulators are used. Another similarity is to be found in the method pursued for cooling the furnace roof, where the electrodes enter the furnace.

The *operation* of the furnace and, with it, the duration of the treatment, is much the same with the Girod furnace as with the Héroult. This applies as long as hot charges are being treated, for when it comes to melting cold charges, the Girod furnace shows undeniable advantages over the Héroult furnace. This is because the vertical path of the current does not permit any short circuits at almost full voltage, when the upper electrode touches the top of the scrap pile. When the electrode is lifted clear of the furnace, the scrap entirely fills its interior, and the short circuits are avoided, as the current path necessarily makes a multitude of small arcs between the various pieces of scrap. This equalizes the heating of the whole furnace content, thus causing the whole charge of scrap to gradually collapse and melt. However, it must not be left unsaid that the above conditions are present only when the scrap is charged into the furnace as the best operating conditions of the furnace demand; that is, the scrap is not to be thrown in arbitrarily. The most advantageous condition for melting cold stock is when this is in the smallest of pieces, and the conditions become more disadvantageous with the growing number of larger pieces. For these latter offer far too little resistance to the current, if the above method were used by starting with the upper electrode touching the top of the scrap pile. Similarly it is always necessary to spread a layer of the smallest sized scrap on the hearth, so that good contact can be made from the start with the bottom electrode, the end of which naturally lies a little low after the furnace has been in operation for a while. In order to make a good contact possible between the bottom electrode and the charge, care must be taken that no slag remains in the indentation over the iron electrode, otherwise this cold slag would act as a conductor of the second class, and in this state act as an insulator.

We now come to the *electrical conditions* of the Girod furnace. Heretofore this furnace has been built mostly in two sizes. The smaller size of 2½ tons capacity shown by Fig. 61 and the larger

size of 10 and 12 tons shown by Fig. 62. The smaller furnace takes about 300 Kw. and the larger from 1000 to 1200 Kw. As the current is only interrupted by one arc the resistance of the whole circuit of the Girod furnace is comparatively small. From this it follows that a comparatively low voltage suffices, in order to give the furnace its needed energy. The voltage therefore for the 300 Kw. furnace is from 60 to 65 volts, and with the 1000 to 1200 Kw. furnace it is 70 to 75 volts.

As the furnace has only two poles, one above and one below the bath, naturally only single phase current can be used. As the Héroult furnaces are operated almost exclusively from 25 cycle circuits, so the Girod furnaces today operate exclusively from circuits of this periodicity. The first trial furnace of 1½ tons tapping weight operated from a 35 cycle circuit, using 40 to 60 volts, 4000 to 6000 amperes and giving a power factor of .65%.

The low voltage of the Girod furnace naturally necessitates a comparatively large current, and with it very considerable cross-sections in the conductors between the furnace transformer and the furnace. This is very noticeable when comparing the furnace with a Héroult furnace having an equal charging capacity and the same power input. It is this lower voltage which makes this part of the installation more expensive than would be the case with a furnace having a higher operating voltage. We must, however, take into consideration that the lower voltage also has its advantages. We only mention the fact that it is easier to insulate this voltage from the furnace refractories, and there is less danger for those operating the furnace.

It has already been remarked that the Girod furnace is the youngest among the better known arc furnaces. It is therefore not to be wondered at, that it is not yet absolutely clear how best to *operate the furnace.* This is why we find in the comparatively sparse literature on the Girod furnace, the recurrent opinion that the Girod furnace is radically different from the Héroult, owing to the fact that the bath is connected in the circuit in a different way. We have already alluded to the advantage of the current

passing through the steel and iron in a vertical direction, when melting cold scrap. We desire, however, to discuss the operation of the furnace when the charge is melted.

As we have seen, the current passes through the bath in a horizontal direction, in the Héroult furnace, and in a vertical direction in the Girod furnace. With the Héroult furnace, however, mention is never made of any essential influence of the purely resistance heating, which occurs because the current must overcome the resistance of the bath, yet with the Girod furnace we often find an important heating effect ascribed to it. In order that there shall be no misunderstanding, it may be said that the different manner in which the current goes through the bath in both furnaces causes different effects, yet these effects do not cause a greater or less resistance heating, (caused by the current passing through the bath,) but rather a difference in the circulation phenomenon. This may be decidedly more advantageous in one case than in another. To which misleading points of view our opinions lead us to suppose that the resistance heating, (even with a molten bath,) is of considerable influence, is shown in a short article on the Girod furnace in *Stahl und Eisen*, for 1908. Here it is pointed out that the depth of the melted iron of the Girod furnace may easily be increased from 30 *cm.* (12 inches), to 75 *cm.* (30 inches), or more. With all this the pure resistance heating is supposed to heat the whole bath evenly throughout its total depth. In spite of this, though, Girod with his 10- to 12-ton furnaces only used a depth of bath equal to 30 *cm.* (12 inches).

A large surface bath has much greater radiation losses as a consequence than a bath has, having great depth and a lesser surface. The above example of the 12-ton furnace really proves that the resistance heating in a Girod furnace can be entirely ignored, as soon as the furnace content is molten. We can also convince ourselves of this arithmetically.

If we take, for example, the 2½-ton Girod furnace, we find by consulting Fig. 61, that with a depth of bath equal to 240 mm. (9.1 inches), the average bath cross-section is about 1200 × 1200 sq. mm. (48 × 48 sq. inches). If we take the specific resistance

of the bath at 1.66, as given on page 15, we find the ohmic resistance of the bath,

$$= \rho \times \frac{l}{q} = 1.66 \times \frac{.24}{1200 \times 1200} = .28 \times 10^{-6} \text{ ohm.}$$

A furnace of this kind takes about 300 Kw. at 60 volts. With a power factor of .8% it gives a current of

$$\frac{300{,}000}{60 \times .8} = 6250 \text{ amperes.}$$

The energy, therefore, transformed in the bath is:

$$i^2 \times r = 6250^2 \times .28 \times 10^{-6} = 10.94 \text{ watts.}$$

This amount is only $\frac{3}{1000}$ of 1% of the 300,000 watts delivered to the furnace, and everybody must admit that any such small amount of energy has absolutely no effect on the heating. If, on the other hand, we figure the current density in the bath, we will see that this comparison also shows the heating of the molten metal to be entirely uninfluenced by the current flowing through this resistance, and that the resistance heating of the carbon electrodes is much more important than the resistance heating in the bath. The example we have before us gives, $\frac{6250}{1200 \times 1200} = \frac{6250}{1{,}440{,}000} = .0044$ amperes per square millimetre $\left\{ \frac{6250}{48 \times 48} = \frac{6250}{2304} = \begin{matrix} 2.71 \text{ amperes per} \\ \text{square inch} \end{matrix} \right\}$ which allots 230 sq. millimetres to 1 ampere (about .36 sq. in. per ampere). If we compare this with the current density in the carbon electrode, which conducts the same current that flows through the bath, and has a cross-section corresponding to a diameter of 350 mm. or 96211 sq. mm. (13¾ inches dia. gives 149 sq. inches) with the 300 Kw. furnace, we observe that we only obtain a cross-section per ampere of $\frac{96211}{6250} = 15.4$ sq. mm. $\left( \frac{149}{6250} = \begin{matrix} .024 \text{ square in.} \\ \text{per ampere.} \end{matrix} \right)$ With all this it is well to note that the comparison of these absolute values gives a much too favorable picture, because no consideration has been taken of the higher specific resistance of the carbon compared to the iron bath. In accordance with

data on page 15, we figured the specific resistance of fluid iron as $\rho = 1.66$. This resistance refers to a length of 1 m. (39.37 inches), and 1 sq. mm. (.0155 sq. inch), cross-section. With electrodes in the operating condition we figured $\rho = .0056$ (see page 130). This value corresponds to a length of 1 cm. (.4 inch), at a cross-section of 1 sq. cm. (.155 sq. inches). If we convert this value to one corresponding to a length of 1 m. (39.37 inches), with a cross-section of 1 sq. mm. (.0155 sq. inches), we acquire the value for carbon in the operating condition, when $\rho = 56$. That is to say, the specific resistance of the carbon is $\frac{56}{1.66}$ or say, 35 times larger than that for iron. From this it follows that even with equal lengths and cross-sections, 35 times as much energy is transformed into heat in the carbon as in the iron bath. It is obvious that the carbon has a much smaller cross-section and a much greater length than the metal has, evincing that the consequent heat distribution is much more unfavorable for the iron, when considering only the resistance heating. The true ratio is therefore not apparent by the above partial calculation.

We will now consider the *comparison* of this furnace with the ideal furnace. We first come to the *availability of any kind of alternating current* and refer again to the former remarks, that single phase current is only available for this type of furnace, as the use of three phase current would come in conflict with the principle underlying the furnace design. In case a single phase generator is not specially installed in the power-house, and should it be desired to operate from an already existing power system, then it is necessary to furnish a rotary transformer. This latter would then convert the prevalent three phase current or direct current into the desired single phase alternating current. Alternating current is usually generated at a commensurately high voltage, brought to the vicinity of the furnace, and there transformed into a stationary transformer to the wished-for low tension current for the furnace.

It is just as difficult to entirely avoid the *power fluctuations* with a Girod furnace as it is with a Héroult furnace; yet it is to be observed that with the Girod furnace the current fluctuations

in actual practise are neither as violent nor do they occur as often as they do in the Héroult furnace. In spite of the current fluctuations being smaller, they are yet important enough in a 2½-ton Gi od furnace which takes 400 Kw. on an average with a power factor of .80%, to recommend that a 500 to 550 Kw. machine be employed. This example may properly show why the initial cost rises which really becomes noticeable here, all due to these power fluctuations. Finally, we may again mention, that the automatic regulation is accomplished by means of Thury regulators. With Girod furnaces, these regulators are set to keep the current constant, and they in turn give the electrodes their proper setting.

The easy *regulation* of the incoming energy in the Girod furnace is the same as with all other electric furnaces.

The *electrical efficiency* of the furnace is influenced, *first* by the probable installation of a rotary transformer, latterly, by the losses of the stationary transformer, (neglecting the losses in the conductors,) and finally by the losses at the furnace, due to the electrodes. For a general calculation we can use the following values:

| | |
|---|---|
| Efficiency of the rotary transformer | 85% |
| Efficiency of the stationary transformer | 96% to 97% |
| Efficiency of the carbon electrodes including the heat conduction losses | 90% |

All Girod furnaces are made of the *tilting variety*. The hearth is easily surveyed, and perfectly accessible for all operating conditions.

We now come to the *circulation* of the melted metal and once more to the fact that the peculiar path of the current in a Girod furnace is of added importance. This circulation begins with one or more current centres above the bath, and goes to the bottom electrodes set around the periphery of the furnace. Figs. 63 and 64 show the diagrammatic connections for the current paths in a Girod furnace, Fig. 63 being the plan view and Fig. 64 showing the cross-section at *a b*. The dots and crosses indicate the lines of force, which follow the arrows according to the laws given in Chapter III. As lines of force of the same direction

repel while those of opposite direction attract, and as the molten bath in a certain sense can be regarded as a movable conductor, with the vertical electrodes over and under the bath considered as fixed conductors, we find in the molten steel certain circulation phenomena, as shown by the arrows in Fig. 64. That is to say, a definite circulation will appear throughout the entire bath, of such a nature, that a current of metal can be observed going

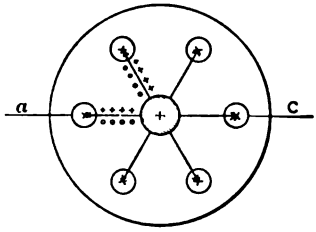



FIG. 63.

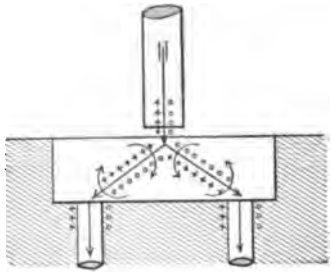


FIG. 64.

from the walls of the furnace toward the centre, from there to the bottom, and back again to the walls. The strength of this circulation phenomenon depends on one hand on the strength of the current which flows through the bath that is then collected at the electrodes, and, on the other hand, on the depth of the bath. For it is evident that the circulation in the bath would instantly cease if the metal currents were in a vertical direction, instead of being in an almost horizontal direction. If the bath has a comparatively great depth, we would approach the vertical direction condition. We ascertained before, that as the heating in a Girod furnace is practically entirely from the arc, a great depth of bath is therefore precluded, so we see now that the advantageous mixing in the bath would cease if this were, say, over 40 cm. deep (about 16 inches) this adequate mixing being present with shallow baths or those of normal depth.

The *application* of the Girod furnace for the steel industry is one of the widest. It has already been said that very good results are obtained with furnaces of the 12-ton size. Here however, they already use four electrodes of considerable cross-sections.

There is then no reason why Girod furnaces cannot be built of the same capacities as, for instance, the Héroult furnaces, even though the Girod furnaces operate with a lower voltage than the Héroult furnaces, and although the latter operate with three phase current, which has not yet been used for the former. In order to show this, we will assume having 1200 Kw. energy at .80% power factor, to be used by means of three phase current at 110 volts on the one hand and at single phase current at 70 volts on the other, in the former case for a Héroult and the latter case for a Girod furnace.

Then, per phase, we obtain for the three phase Héroult furnace, a current of

$$i_h = \frac{1200000}{110 \times 1.73 \times .8} = 7882 \text{ amperes,}$$

and for the single phase Girod furnace the current:

$$i_g = \frac{1200000}{70 \times .8} = 21429 \text{ amperes.}$$

Now *Héroult* has to deal with 7882 amperes for each phase, *i.e.*, three electrodes are needed each to cary 7882 amperes, whereas Girod has only to carry once a current of 21429 amperes. Suppose we assume that he too uses three electrodes, connected in parallel of course, then each would carry a current equal to $21429 \div 3 = 7143$ amperes. In other words, it would even suffice Girod to have a lesser total electrode cross-section than Héroult, though the latter has a much higher current in the electrodes at the same current density. Or we may say: "The influence of carrying the current in, one way or another, is of so little importance as regards its effect on the carbon electrodes, and that the electrode relation in both types of furnaces may be regarded as being exactly like." Therefore, the same reasons governing the maximum size of the Héroult furnace cover the Girod furnace also, so that the attainable size of either furnace is on the same footing. A certain limitation of the applicability of the Girod furnace may arise in certain cases, as the furnace so far has only been built for single-phase current, which necessitates expensive rotary transformer units for large furnaces, if the

current of an existing three phase central station is to be used. If no consideration need be taken of an existing power plant, even then the single phase generators for large Girod furnaces will be more expensive than three phase machines of the same size for Héroult furnaces. Regarding the *uninfluencing effect of the electric heating* on the chemical composition of the bath the comment given on page 137 is also applicable here. This applies to all arc furnaces which have their electrodes directed directly against the metal to be treated.

Especially worthy of mention with the Girod furnace is the influence which the water-cooled bottom electrode exercises, even though this influence is said to be of no consequence. To understand this, consider that the circular motion in the bath also continually renews the coldest material over the bottom electrode, so that in spite of the greater temperature difference between the bath surface and hearth bottom, there remain practically the same conditions as in the Héroult furnace.

In coming now to the *consummate efficiency* of the Girod furnace, it may be again said that, compared to the Héroult furnace, the proportions of the carbon electrodes in both furnaces may be looked upon as being equal to each other. From this it follows that not only are the electrical losses equally great, but the thermal losses also, for these are caused by the hanging carbon electrodes. Also, the water-cooling losses, caused by the devices at the roof of the furnace, where the carbon electrodes pierce it, are by no means unimportant. According to the report of Conssergues, these are about 10%; for it was established that the power consumption with the Girod furnace decreased 10% when it was operated without the water cooling. The fact that water cooling apparatus is used today on all Girod furnaces as well as on all other arc furnaces, may be explained by the following reasons, (as discussed on page 100,) first, a tighter fit can be made at the water cooling entrance to the furnace, the electrodes being better protected against oxidation, and, secondly, because the water-cooled boxes allow the furnace roofs to be stiffened, which latter have their life considerably prolonged. Besides

these roof and wall radiation losses of the furnace which are about equal in the Girod and Héroult furnaces, there remain still to the detriment of the Girod furnace the losses of the water-cooled bottom electrode. These are avoided in the Héroult furnace.[1] We come to the conclusion, therefore, that the losses due to the cooling of the bottom electrode are—according to an address by *Trasensters*—"much less important," than those which are occasioned by the cooling where the roof is pierced for the carbon electrodes.

In order to further judge the total efficiency of the Girod furnace, the following notation is taken from a report of the firm, Öhler & Co., of Aarau, in Switzerland. (See *Electrochemical and Metallurgical Industry*, 1908, pp. 452 and 453.) Here we first find a description of Girod furnace installation at the above works. The furnace is connected to the power of the municipal power plant, through the medium of a motor-generator set. The 2000 volt, 2 phase current system supplies the Öhler Works' motor of 450 HP, running at 560 R.P.M., and is coupled directly to a single-phase alternator giving 4600 to 5000 amperes at 65 to 75 volts and a frequency of 37.4 periods per second. Twelve heavy copper cables, each 20 mm. in diameter and composed of 12 copper wires twisted together, carry the current 10 metres to the furnace. The voltage drop is 2.5 volts from the machine to furnace, so that this short cable installation alone causes a loss of 3 to 4%. At the end of this report we find this statement. It is calculated that the electrical part of the plant has an efficiency of 75 to 80%; *i.e.*, 75 to 80% of the energy of the primary current appears as heat in the furnace. A rather approximate estimate of the calorific

[1] With the same construction of the Girod furnace as the Héroult, other things being equal, the efficiency of the Girod furnace must be just that amount less, which corresponds to the water cooling of the bottom electrode. According to *Stahl u. Eisen*, July 20, 1911, by A. Müller, in a 3-ton Girod furnace, a calorimetric determination of the heat carried out in the cooling water of these bottom electrodes gave 10.1 kilowatt-hours for the 130 minute run and about 1.01 per cent., or 2.9 kilowatt-hours per ton of steel produced. The cooling water used in the top electrode carried out 36.7 Kw. hrs., 3.65% of total energy supplied or 10.5 kilowatt-hours per ton of steel.

efficiency of the furnace itself shows about 50% of the current converted into useful heat.

Naturally the efficiency with the Girod furnaces also rises as the furnace increases in size. Yet, it is to be noted that, when the number of the upper electrodes is increased, the efficiency curve decreases here as well. The reasons underlying this were given in the preceding chapter on the Héroult furnace.

The *costs* of a 2½-ton Girod furnace including the electrode regulators, the switchboard instruments, the tilting mechanism, its motor and short conductors between the furnace and its transformer or the dynamo room, total, according to Borchers, about $3,000. A large furnace of 10 to 12½ tons with the same equipment will cost about $7,000.

The cost of a complete Girod furnace installation, but exclusive of the transformer or generator, and consisting of an operating and a reserve furnace each of 2 tons capacity, together with the necessary equipment for pouring the steel, and the accompanying buildings, total, according to Borchers, about $40,000 to $60,000. An installation with a 10- to 12½-ton furnace and a reserve furnace of the same size will cost about $60,000 to $80,000.

The *power consumption* with the Girod furnace is about the same as that given for the Héroult furnace. What differences there may be due to a more or less favorable efficiency can be omitted when making arithmetical calculations, as the power consumption figures depend largely on the efficiency of the furnace, as well as on the charge and the final product. The composition of the final product produces much greater variations in the power consumption, than the differences in the efficiency. This, of course, does not hinder the furnace with the better efficiency to operate with less power and consequently with lower current costs, provided that an equal start is made with like raw materials, and like final products achieved.

The *electrode consumption* with the Girod furnace may be taken to be the same as with the Héroult furnace, for there is no reason why the electrode consumption should be less with one furnace than with the other, when about the same electrode

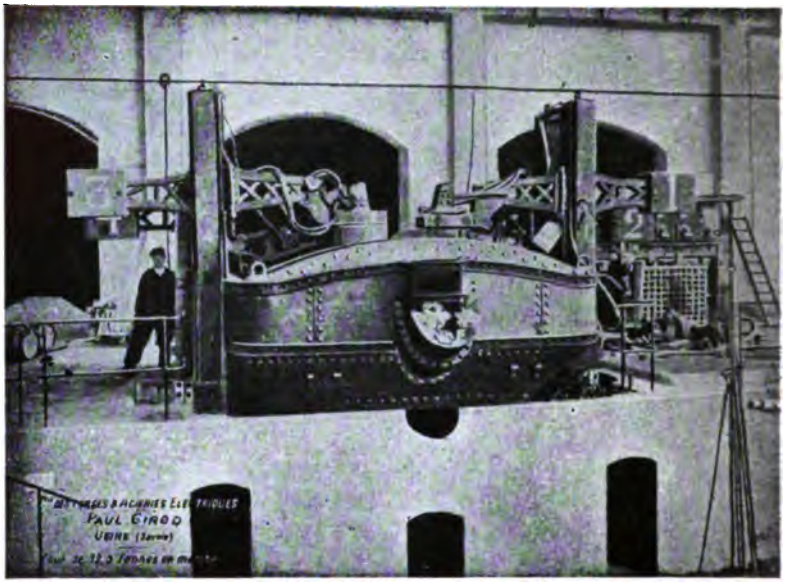



FIG. 65*a*.

FIG. 65*b*.

cross-sections are used in either case. Should there be given, nevertheless, larger or smaller values for the consumption figures, in one case or another, the larger wear can, in no case, be based on the principle of the furnace. Consequently if one furnace is to have any advantage over the other, it must depend on its more or less successfully constructed details.

In order to give the reader an idea what these furnaces look like, Figs. 65*a* and 65*b* are shown, for these picture a 12½-ton furnace as it is operated at Ugine, France.

As the preceding chapter on the Héroult furnace was closed with Héroult's own opinion of the advantages of his furnace, so this chapter is closed with the deduction of Borchers, where he proves the superiority of the Girod furnace over the Héroult furnace. The quotation is taken from *Stahl und Eisen*, 1909, page 1947, where Borchers says: "I strictly maintain that today there is no electric furnace for the refining of metal which excels the Girod furnace. I make special reference to the uniformity of the current distribution; the uniformity of the heat generation in the bath; the low voltage between poles, the consequent lesser insulation difficulties; followed by the consequent lesser danger to the operatives; on account of these circumstances, it excels in its simplicity of construction as a whole, and in its operation."

It is well to compare this with the opinion of Héroult given on page 142. Lastly we may add that, if we consider only the evenness of the current distribution, and the heat generation as above mentioned, these alone should be enough to decide the question. That there is an advantage in the lower voltage goes without saying. To these we might add the further advantages of the smaller current fluctuations, especially when melting down cold stock, while the opinion regarding the greater simplicity and the greater safety during the operation of one furnace over the other, may be left to the reader. Regarding the application of the Girod furnace, reference is had to the statistics in the closing chapter. Licenses for Girod furnaces may be had from the inventor, Paul Girod, Ugine, Savoy, France, or from his American representative, C. W. Leavitt, New York.

# CHAPTER X

## THE INDUCTION FURNACE IN GENERAL

It was demonstrated in Chapter IV that an insulated wire of a coil carrying current generates lines of force, and that these lines or fields of force, are continually alternating, when alternating current flows in the coil. These alternating lines of force constitute the well-known underlying principle for all induction phenomena. It is therefore evident that in an electrical conductor which lies in the field of another conductor, a current will be induced, which will be proportional to the number of lines of force cut in unit time.

This fact immediately gives us the information, by the aid of which we are enabled to obtain any current strength by induction. We merely have to oversee that the conductor in which we desire to induce the current shall be cut with as many lines of force in unit time, as will give the wished-for current conditions.

In order to achieve this we encounter these various possibilities:

Imagine a certain number of lines of force, raised to twice their strength. Then we should find that a turn of wire, lying in this magnetic field, would have twice the electro-motive force generated in it as in a field of only the original strength. When the magnetic lines are doubled, then, the conductor is cut with twice the number of lines of force in the same time.

The same effect is accomplished, however, when the field is kept at its original strength, if two turns are used instead of one, where they are both cut by the same number of lines of force. What we have then in this case is an increasing number of turns, and with it a raise in the voltage in the induced coil; because for the moment we may think of these two turns as being separated in such a way, so as to give us two separate turns, each

having the same voltage that one turn has now. Finally the potential in the induced circuit may be increased, by raising the velocity of the current alternations, and this leads us to a change in the frequency. And as the induced voltage is proportional to the velocity of the alternating lines of force, it is evident that, a current of 50 cycles will give twice the induced voltage a current of 25 cycles will give, other things being equal.

If we now combine the three methods into a formula, which influence the conditions in an induced circuit, we obtain—

$$e = C \times \nu \times s \times N$$

where $e$ denotes the voltage
$\nu$ denotes the frequency
$s$ denotes the number of turns
$N$ denotes the number of lines of force
and $C$ is a constant.

We have so far assumed that our lines of force, generated by the aid of a wire coil, sought their paths through the air. This arrangement is, however, very disadvantageous because the air is a very poor magnetic conductor (being only 1/180 as good as iron). The lines of force in this way seek the shortest path, resulting in the consequences (for instance, with a coil of a great number of turns) that only a part of the turns are cut by the total number of lines of force, whereas for the remaining turns only a part of the total lines are taken into consideration at all. In order to keep the lines of force from spreading, or straying, as it is called, we provide a good magnetic conductor for them, which forces them to take advantageous and predetermined paths, due to the high magnetic conductivity, which in turn gives a good inductive action. These things give us the so-called transformer.

Fig. 66 shows the principal arrangement of a transformer as it is commonly used, as well as for induction furnaces. In the figure, $K_1$ and $K_2$ denote the transformer cores, and $J_1$ and $J_2$ the yokes. The wire coils are wound on these cores. The coil receiving the current from an outside source is called the primary, and the coil delivering the useful current is called the secondary

winding. Both coils are separated from each other by suitable insulation.

If these yokes and cores were made from solid pieces of iron, then it would not be possible to avoid the considerate losses due to eddy currents, as set forth in Chapter IV. Therefore, in order to bring these losses down to the smallest percentage, the iron cores and yokes are built up of many thin sheets of iron of

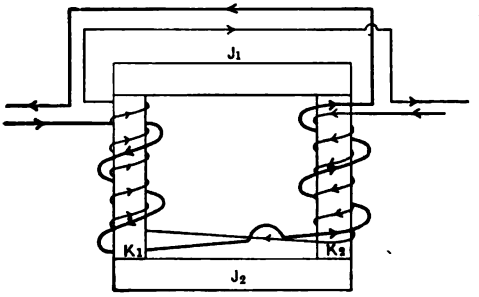



FIG. 66.

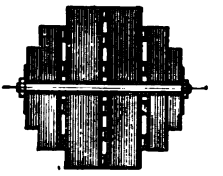


FIG. 67.

.3 to .5 mm. (.012 to .02 inches) thick. These sheets are insulated from each other by pasting sheets of paper on one side, about 1/10 as thick as the sheet iron, and the whole then held together by means of screws. Large core cross-sections are divided into separate divisions, which are kept apart by so-called ventilating ducts, by means of which the already low hysteresis and eddy current losses and their consequent heat generation are nullified. Fig. 67 shows one of these core cross-sections.

If the primary coil of a transformer is energized with an alternating current, which must necessarily produce an induced current in the closed secondary circuit, then the iron core will be permeated with magnetic lines of force, which is common to both coils. As the primary and secondary coils, besides this, must have the same frequency, we obtain the equations for the voltages in both coils, as follows:

$$e_1 = C \times \nu \times N \times s_1$$

and

$$e_2 = C \times \nu \times N \times s_2$$

from which it follows that:—

$$\frac{e_1}{e_2} = \frac{s_1}{s_2}$$

In this ratio we call the factor $\frac{s_2}{s_1}$ the *ratio of transformation.*

The equation signifies that:—

*The voltage is proportional to the number of turns.*

By applying a different number of turns in a transformer, we obtain a means whereby any existing voltage may be changed into any other voltage, and one thus suitable for the operation of electric induction furnaces.

In this way transformers are nearly always used in alternating current installations. For this method makes it possible to transmit power over great distances at high voltages and at small currents, thus using only smaller and cheaper conductor cross-sections, from the central station to the point of power consumption. At that place then a transformer is erected, by the aid of which, the high primary voltage is changed to any desired secondary voltage, which may be most advantageous for the particular apparatus.

We have already observed that transformers are used in this way for arc furnace installations. Alternating current provides such a convenient way of transforming energy in stationary transformers, and this together with its lack of chemical influence constitute the two factors responsible for the reason that all arc furnaces are operated with alternating current to-day.

With the present technical perfection of the transformer this last may be regarded as a sort of interposed apparatus, which produces at a different voltage, almost the same amount of energy which it receives. That is to say, the losses in a transformer are extraordinarily small. With transformers of more than 50 kw the losses are from 2 to a maximum of 3%. Even though the efficiencies of transformers for electric furnaces will fall slightly on account of the necessary overload capacity, yet we may consider, for the sake of simplicity, that the total primary power is given up in the secondary circuit.

Then the primary power $p_1 = e_1 i_1$,
and the secondary power $p_2 = e_2 i_2$,
where $p_1 = p_2$ and consequently $e_1 i_1 = e_2 i_2$.

From this it follows that

$$\frac{i_1}{i_2} = \frac{e_2}{e_1} = \frac{s_2}{s_1}$$ that is:—

*The current is inversely proportional to the voltage and inversely proportional to the number of turns.*

The foregoing conclusion is of the greatest importance for it solves the building problems of induction furnaces. Induction furnaces in reality are nothing more nor less than properly designed special transformers. Hence every induction furnace has its iron core and yoke, to carry the lines of force, and a primary winding, wound over one part or another of the iron core. On the other hand, the secondary winding is composed either entirely or for the most part of the bath itself.

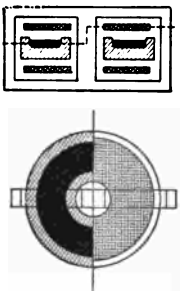


FIG. 68.

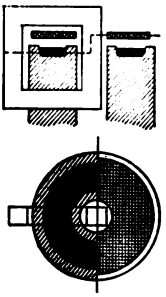


FIG. 69.

This point of view enables us to group electric induction furnaces—on the one hand into those furnaces where the secondary winding is composed entirely of the bath; and on the other hand into those where, besides the bath being the secondary winding, there is still another winding, made of copper to aid the heating. We denote the former as *simple induction furnaces* and the latter as *combination furnaces*.

If we take up the first group of simple induction furnaces, we see that the different methods of construction can be distinguished merely by the way the primary coil is placed, relative to the bath. The Figs. 68 to 72 show a number of the most prevalent suggestions. In the figures the steel bath is denoted by the solid black, (the layer of slag is not shown,)

the refractories by inclined hatching and the primary winding by cross hatching. Figs. 68 and 69 show the primary winding in the form of large radial disks, which are under or over the bath, or as Fig. 68 shows it to be both under and over the metal. On the other hand, Figs. 70 and 72 shows the primary winding in the form of a long cylinder, which is placed inside or outside of the ring-shaped hearth. With this arrangement we speak of transformer with *cylinder* or *tube winding* and those of Figs. 68 and 69 as having a *disk winding*.

In all cases the principle of transforming the energy is the same, and in all cases we shall find the ring form hearth, in whose contents the heating currents are produced by means of induction, quite independent of the place in the magnetic circuit, occupied by the primary winding. It is evident that any of these winding schemes can be combined with every other method, and we may therefore state that there is no combination of windings and no placing of it at some part of the transformer, that has not already been patented as being particularly good.

It has been shown that we are enabled to obtain any desired current strength in the secondary circuit, by properly winding the primary. The first one to recognize these conditions and use them in the design of an electric furnace was de Ferranti[1],

[1] In this connection proper credit must also be given to Colby. Many years after the invention was made, the Franklin Institute investigated the early patent applications of both Ferranti and Colby and reported, in 1911, in part, in speaking of the patents, as follows:

See British patent to Ferranti, No. 700, Dec. 16, 1887, filed January 15, 1887.

U. S. Patent to Colby, No. 428,378, May 20, 1890, filed April 14, 1887.

U. S. Patent to Colby, No. 428,379, May 20, 1890, filed Sept. 19, 1887. . . .

Between the years 1890 and 1900 no notable application of the process appears to have been made. . . .

Colby's furnace is most broadly described in his U. S. Patent 428,379.

It appears evident that the applicant was one of the first to devise the elemental features of the induction furnace. . . .

It is generally conceded that the basic use of the transformer principle to electric furnaces was independently applied by both Ferranti and Colby, the dates of their patent applications being but a few months apart. The tubular water-cooled conductors, the means of supporting them and the connecting devices constitute essentially the features of novelty in the most recent patent

who patented his apparatus, as shown schematically by Fig. 68, in 1887. Even though his design was never put to practical use, we see how completely de Ferranti and Colby had at that time mastered the problem of heating by induction currents.

If we use the furnace form as shown in Fig. 68, in order to obtain a clear view of induction heating, we observe that the middle core of the transformer carries the primary winding and that the furnace hearth is arranged concentric with this. There

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of Colby. . . . The forms of induction furnace depicted in the early Colby patents closely resemble those adopted in present-day apparatus and although but a joint pioneer in this field, his original designs are distinctive in anticipating the subsequent state of the art.

In consideration of its originality and wide and successful commercial use, the Institute recommends to the Philadelphia Board of City Trusts the award of the John Scott Legacy Premium and Medal* to Edward Allen Colby of Newark, N. J., for his Induction Electric Furnace.

Adopted at the Stated Meeting of May 3, 1911.

(Signed) WALTER CLARK, President,
R. R. OWENS, Secretary.

GEO. A. HOADLEY, Chairman of the Committee on Science and the Arts.

* Medal shown herewith:

FIG. 69*a*.—Facsimile of medal awarded to Colby for his induction furnace by the Franklin Institute.

is no secondary winding of copper such as we usually find with ordinary transformers. Should the ring-shaped hearth be filled with molten iron, as shown in the figure, we may regard this ring of iron as the secondary winding, which is composed of only one single turn. Induced currents will, therefore, appear in this iron ring, the same as they would in every other electrical conductor which lies in an alternating current magnetic field.

As the iron ring comprises in itself one short-circuited turn—or a short-circuit—consequently all of the energy of the secondary circuit is transformed into heat, as the secondary current has to overcome the resistance of the iron bath. The heat quantity generated is proportional to $i^2 r$, that is, it is proportional to the product of the square of the current and the resistance. As the resistance of the iron bath may be regarded as being practically constant for a given charge, it is evident that any desired temperature may be obtained[1] by raising the current and, of course, first of all, by a proper choice of the primary turns; for the secondary turns with these furnaces are always equal to unity.

Suppose we had an induction furnace, possessing 100 turns in its primary winding, and at a definite voltage of, say 1000, it took 100 amperes, we would obtain a secondary current value of

$$i_2 = i_1 \times \frac{s_1}{s_2} = 100. \frac{100}{1} = 10000 \text{ amperes.}$$

On the other hand, if we had a furnace wound with 120 primary turns, and taking the same 100 amperes as before, but at a correspondingly changed voltage, we would obtain a current of,

$$i_2 = i_1 \times \frac{s_1}{s_2} = 100. \frac{120}{1} = 12000 \text{ amperes, in the bath.}$$

These examples show how the number of turns influences the secondary current, and consequently the attainable temperature of the bath. It is, therefore, the part of the furnace designer to so choose his proportions, that he may in any case reach the desired temperatures, for his particular case.

[1] See Am. Electro-Chemical Society, Sept., 1912, paper by C. H. Vom Baur on "Electric Induction Furnaces for Steel," giving an instance where the temperature of steel in an induction furnace reached 2550° to 2600° C.

During the operation it is, of course, precluded that any primary turns of the furnace transformer be changed. Still, during the time of operation, temperature changes are desired, which in turn calls forth changes in the energy absorption of the furnace. But even these changes are easily made. We have only to realize that the load on the furnace transformer is brought about solely by the particular resistance of the iron bath, which we may consider as a constant factor for a definite charge. It is now apparent that we have in Ohm's Law $i = \frac{e}{r}$, a simple remedy for changing the energy, and thereby the current, by simply altering the voltage for the primary winding.

Necessarily the secondary voltage and its current are instantly changed as $e_2 = e_1 \frac{s_2}{s_1}$.

If we now review the above, regarding induction furnaces, we find:—

1. The charge in induction furnaces is heated, solely and alone by reason of the current overcoming the opposed resistance, and to any practically desired temperature. The induction furnace is therefore only a particularly favorable type of resistance furnace, which allows a complete and even heating of the metal, without producing any overheating at any point.

2. By changing the primary voltage at any time during the operation of the furnace, the temperature of the charge may be raised or lowered at will, either quickly or slowly. At the same time the heat in the entire furnace contents is altogether uniformly raised or lowered.

If all induction furnaces possess these qualities, what differences are there then between the different arrangement of the windings as far as the molten metal is concerned? (See Figs. 68 to 72.)

It is well to state that the differences between Figs. 71 and 72 are purely constructive, as the double magnetic path halves the cross-section of Fig. 72, opposite the simple path with the whole cross-section of Fig. 71, yet does not in any way produce any new electrical effects. Therefore, these two types of Kjellin

furnaces only differ in their outward appearance, without either one or the other of the iron cores giving any advantages worth mentioning.

Substantial differences may, therefore, only be found in the arrangement of the coils, and these follow different directions. It is evident that the suggestion of Colby, made in 1887, (the

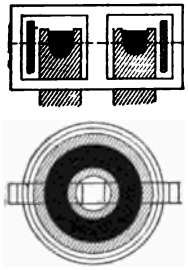


FIG. 70.

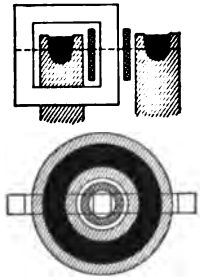


FIG. 71.

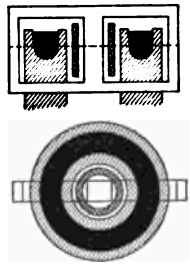


FIG. 72.

first to surround the hearth with the winding,) necessitates more copper conductors than the second suggestion of Kjellin, of 1900, where the primary winding is inside of the ring-shaped hearth. The whole arrangement of the Kjellin furnace, by reversing this idea, is simpler than the Colby furnace, not only on paper, but also in reality. The Colby furnace, as well as the de Ferranti furnace, are today only of historical importance, except for their later existing patents. This leaves only the accomplishments of Kjellin and Frick for discussion.

If we put aside for the moment the fact that the Frick furnace does not permit such a general view of the hearth, or allow the accessibility thereto, on account of the overhanging disk winding, as we have with the Kjellin furnace with its coil removed from the operating conditions, we find that the chief distinction between these furnaces lies in the different circulation of the bath, caused by the changed position of the coil. We saw in Chapter III that the motor effect of an electric current appears, when two conductors with their magnetic fields mutually affect each other. The different position of the winding cannot, therefore, be without its influence on the inclination of the bath surface. As will

be shown in the following chapter, the Kjellin furnace produces the effect of pressing the molten metal toward the outside, so that it stands higher on the outside wall than on the inside. In the Frick furnace, for the same reason, we find a stronger magnetic pressure on the current carrying molten metal, where the bath and the coil are nearest to each other, and this causes the metal surface to be more depressed at this point than the remaining part of the hearth. The Frick furnace, therefore, also has an inclination to its bath surface, so that this stands higher at the outside than at the inside. While this slope in the bath is only 4° 34′ to 5° 5′ with an 8-ton Frick furnace, according to the published report of von Neumann of the firm of Freidrich Krupp (see *Stahl und Eisen*, 1910, p. 1071), we see that with a Kjellin furnace of the same size, that it is 34°. These differences naturally cause considerable deviation in the circulation phenomenon of the bath, so that these are greater in the Kjellin furnace and to its detriment, than they are in the Frick furnace.

Even though there are certain differences between the Frick and the Kjellin furnaces, owing to the different position of the windings, still in the essentials of their operation they are entirely alike. As the Kjellin furnace opposite the Frick furnace has found a much more extended use, it will suffice if we describe the Kjellin furnace in the next chapter as a representative one. In this the secondary coil is composed solely and alone by the hearth metal itself. The honor is due Kjellin for producing the first practically useful induction furnace.

In addition to the group of induction furnaces just mentioned, in which the secondary coil of the furnace transformer is composed entirely by the bath, there is yet a second group of induction furnaces, which has another common copper winding, besides the short circuited secondary turn which is the bath.

This second group of induction furnaces owes its existence primarily to the fact that the furnaces of the first group have a comparatively poor power factor. The cause of this being that the distance between the primary and secondary windings is so

great, that a large number of the lines of force take their path through the air, without being able to affect the secondary voltage. We designate these lines of force as, stray lines or leakage lines, and the phenomena itself is called magnetic leakage, and it is this which operates heavily against the power factor.

The greater the distance between the primary and secondary winding, the larger the magnetic leakage will be, and the lower the power factor. The leakage may be lessened by placing conductors in the path of these leakage lines, in which secondary currents are generated by induction. As these currents, which are generated by induced currents, always have the opposite direction of the primary or incoming current, (as was shown in discussing the self-induction phenomenon on page 44,) they will in turn send out stray lines of force in the opposite direction into the original stray field, and in this stray field the conductors lie. We may look upon this effect as one where the stray lines are pushed back, and in this way the power factor is raised by the coils, which lie in the space between the primary winding and the bath.

Patents show a large number of suggestions, in which secondary copper windings are to be employed, in order to gain the above result. But the fact must not be overlooked that on the one hand a poor power factor increases the initial cost but does not increase the energy losses, and on the other hand the current generation in the secondary winding (to decrease the magnetic leakage) can only be accomplished with energy so it is immediately evident that danger lurks nigh, in curing a small evil with a larger one. This error is shown by all the designs, whose sole object it is to lessen the stray fields, by means of the secondary copper winding, in which the heat which is generated in these coils is not put to any use; on the contrary this results in only enlarging the cooling appliances for the windings, in order to protect them from too high a temperature.

The idea of applying the above-mentioned stray field reducing arrangements to induction furnaces, can hardly be looked upon as induction furnace improvements, (as we have learned to know the furnace in the first group,) as long as no provision is made

to profitably use the currents generated in the secondary copper winding.

This last requirement is fulfilled by the Roechling-Rodenhauser furnace, and, as a result, these furnaces have already come into quite extensive use, whereas all other suggestions to improve the induction furnace power factors from within the confines of the furnace proper are today only on paper.

It therefore seems sufficient within the limits of this book, besides describing the Kjellin furnace, to merely narrate the details of the Roechling-Rodenhauser furnace, not only because these two are the only induction furnaces having found extensive use, but also because a discussion of these furnaces will be sufficient to give the reader a clear idea of the workings of induction furnaces. At the same time it will also enable one to adequately judge the value of any other constructional features.

If in closing we again mention the essential thing about an induction furnace, we find that the characteristic mark of them all is the common transformer.

In the induction furnace we find the application of the *built-in transformer* to be of the greatest importance to the heating method. For in this way only is it possible to generate the strongest currents directly in the iron bath without conduct or losses, so that the molten metal itself may be regarded as the source of heat.

In his addresses before the "Verein deutscher Eisenhüttenleute," *Borchers* says:

"Here in the induction furnace we should truly possess the most perfect of electrical heating. Here the generation of heat goes on solely and alone in the metal to be melted, and in the molten bath; the heat transference from other heat sources to the metal is not first required."

Again when comparing resistance furnaces,—and the induction furnace may be regarded as a resistance furnace,—with arc furnaces, *Borchers* says: "With both furnaces it is possible to reach a temperature of 3500° C. (6332° F.). There will always be 3500° C. at the arc of an arc furnace, while resistance heating enables any temperature up to this point to be reached."

# CHAPTER XI

## THE KJELLIN FURNACE

THE first induction furnace which made a name for itself as a result of its achievements was the Kjellin furnace. It was conceived in 1899; thus the first trial furnace was placed in operation on March 18, 1900. The furnace was only intended for a capacity of 80 kg. (176 lbs.), with an energy consumption of 78 kw. Steel castings could be made with this furnace, only with the extraordinarily high power consumption of over 7000 kw hours per ton of steel. With the second furnace of 180 kg. (about 400 lbs.), which was ready for operation in November, 1900, this amount was reduced to one-third of the original figure. A third furnace followed having a capacity of 1350 (about 3000 lbs.) to 1800 kg. (about 4000 lbs.), which was installed in Gysinge on the Dalelf in Sweden. With this furnace they succeeded in bringing down the power consumption to about 800 kw.-hrs. per ton when making steel from cold scrap, and thus, the Kjellin furnace proved its practical and economical adaptability.

On account of the successful operation of these furnaces, the Kjellin patents were acquired by Siemens & Halske A.-G.- for the principal countries of Europe, and under their guidance these furnaces were soon used to a considerable extent.

*In the construction of the Kjellin furnace*, the part giving it its characteristic appearance is the transformer, which comes up through the centre of the ring-formed hearth. The first successfully useful Kjellin furnace was the one having a capacity of 1350 to 1800 kg. (about 3/4000 lb.). This furnace is shown in its later design in Figs. 73 and 74. The original is of the stationary type. The transformer consists of two vertical cores and two horizontal yokes. These are composed of thin iron

sheets, paper insulated, of the usual transformer construction, so that the magnetic losses are as low as possible. Whereas the yokes and the unwound core of the transformer have a rec-

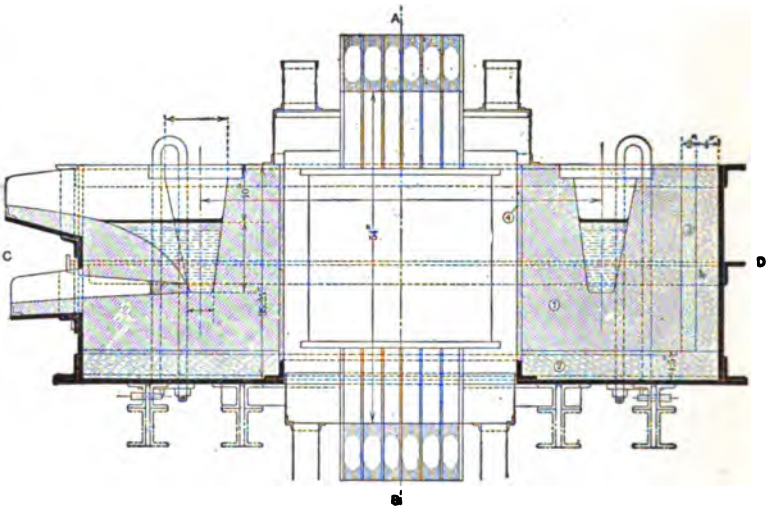



FIG. 73.

tangular cross-section, the core carrying the primary winding is made in the form of a cross (see Figs. 73 and 84). This arrangement permits, on the one hand, a saving in the copper winding,

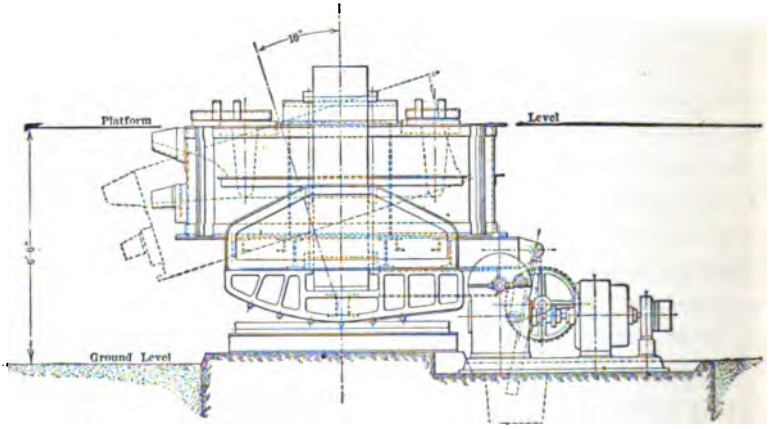



FIG. 74.

as the core is of circular form and easily wound, on the other, it provides for successful cooling of the transformer iron on account of its larger surface and thus favorable cooling conditions are provided. For this Kjellin with his first 1½-ton furnace, used four one-inch tubes which were placed, one each in the recesses made by the section of cross form. These tubes carried an air circulation of 40 mm. (1.6 inches) water gauge pressure in this winding space, which was thus kept at permissible temperature. This air cooling was also taken from the normal transformer design and utilized in this special construction of furnace transformer. Besides this, in order to shield the transformer, and especially the coil from the radiated heat, (from the furnace refractories,) the latter is surrounded with a double walled cylinder of brass of 1½ mm. (.06 inches) thickness. Either cooling water or air is passed through this protective cooling, in order to keep the heat from the winding and the transformer.

The temperature of the cooling water coming from the protective cylinder was measured during operation and showed 40 to 50° C. Naturally this protective cylinder could not be a closed circuit, or if so, it would form a short circuited turn, which would become heated or even melted under the influence of the currents which would be induced in it. In order to avoid this the protective shield is built as an open double walled ring, while in the Kjellin furnace it is bridged over with wood insulation. On the outside of these cylinders we find the furnace refractories or the brick work, in which there is a ring-shaped space concentric with the winding, which comprises the furnace hearth. The furnace shell is of sheet iron and encloses both cores of the transformer.

After the protective brick work has been placed in tne furnace, the bottom is rammed in. Then a templet having the shape of the hearth, is lowered into the furnace, so that the hearth walls of suitable material may be tamped in. When this work is finished the templet is raised and the hearth is practically ready. The hearth roof consists of special bricks, or of small refractory arches held in iron frames, so that they may be easily removed. This is necessary as the furnace has

no doors, and the hearth and the progress of the charge can therefore only be watched by lifting off one or more covers. When the furnace is made of the stationary type, it must necessarily have the stationary type spout.

Subsequent to the design of the first Kjellin furnace as just described, the following constructive changes were made:

In order to allow of a thorough cooling of the transformer, it was divided into a number of smaller divisions, which were separated by means of suitable air spaces. This was only following good transformer practise, and the separate sheets were, of course, paper insulated as usual. The air cooling was changed so that there was a more uniform cooling, not only of the transformer iron, but also of the coil.

The water cooling of the protective cylinder was avoided and air cooling substituted, this coming from the same ventilating fan feeding the coils. This simplified the furnace construction considerably, and gave equally safe operating conditions.

The furnace was made of the tilting variety which materially bettered the conditions for teeming. It may be of interest to mention that Kjellin furnaces have been constructed as though they were self-heating pouring ladles, with which, for instance, the metal could be taken from the open hearth furnaces, then refined and finally poured from the furnace directly into the ingot moulds.

The *operation* of the furnaces is primarily influenced by the fact that the molten metal serves as the secondary winding. Therefore as long as the metal does not possess a conductivity giving an operating voltage having a sufficient heating current, the heating of the furnace by electrical means is impossible. These conditions are the determining factors for the heating of the furnace. As the hearth is of the ring form, it is not feasible to heat the furnace with coke. Care is therefore taken with Kjellin and all other induction furnaces to heat them up with rings of material later to be melted. For making steel, these rings may be cast, welded, or even screwed together, and laid in the furnace. As soon as the current is turned on, induced currents arise in the iron rings, as they become short-circuited

secondary windings. The iron is soon brought to redness, so that the heat thus produced can be used to warm up the furnace. As soon as the furnace walls are red hot, the furnace is charged with fluid metal, and the heating rings are subsequently melted. When this is accomplished, the furnace soon reaches the proper temperature so that the normal furnace operation may begin. If the furnace is operated with hot charges, as is often the case with Kjellin furnaces operating in conjunction with open hearth furnaces, the furnace is fully emptied after each charge and then charged again with open hearth metal. It is evident that it is possible to fully empty the furnace after each charge. Then when the fluid metal of the new charge, immediately makes a closed ring again, the heating begins simultaneously, provided the primary circuit is closed.

The conditions are different when the furnace is charged with cold material. If, under these conditions, the furnace was completely emptied, and a ring made of a large number of pieces of cold scrap, its resistance would be so great, that the proper heating currents could not exist. In this case, it would be found useless to try to obtain a melt. It might, however, be possible to raise the secondary or bath voltage sufficiently, so that arcs would appear between the many small pieces of scrap. In such an event we would obtain heating methods similar to those employed when melting down cold scrap in the Girod furnace. The raising of the voltage necessary to do this, however, leads to difficulties in the transformer design. For this reason, therefore, when working with cold stock, a sufficient portion of the previous charge is left in the furnace to form a closed circuit. If the furnace is now further charged with scrap, it will be melted down by the heat generated in the metal from the previous charge. In this case the cross-section of the bath grows, and a greater absorption of energy takes place, thus hastening the melting. A very quiet melting together of the charge occurs in this way, without any sudden power fluctuations. As there is always a molten remainder in the furnace when using the method of cold charging, it is of advantage to keep this remainder as small as possible; still it must be large

enough to render certain the closing of the molten secondary circuit. The smaller the section of the lower part of the trough, the easier it is to accomplish this. For this reason it is well to make the channel ∇-shaped.

It was previously mentioned that cold charges are melted down without any current fluctuations taking place.

We now come to the *electrical conditions* existing in the induction furnace. If we look a little closer at the current conditions of the Gysinge furnace, we find that for its operation there is provided a 300 HP water-wheel driving a direct connected 165 to 170 kw, 15 cycle, single-phase generator of 3000 volts. When the furnace content is 1350 kg. (about 3000 lb.) the power factor is 80%, and with a content of 1800 kg. (about 4000 lb.) it is 68%.

Even these figures show the dependence of the power factor on the size of the charge with Kjellin furnaces. This is also substantiated by the curve in Fig. 77, which was made from results taken from a Kjellin furnace having a maximum capacity of 8½ tons. This shows, too, how (with other electrical conditions remaining the same), the power factor becomes lower

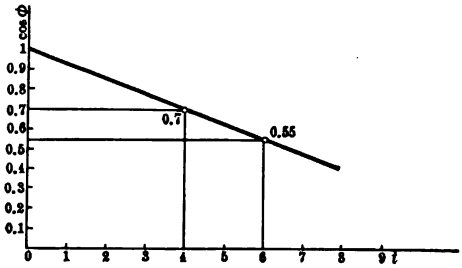



FIG. 77.

with an increased charge. We can, therefore, establish the fact that:—"*With the same frequency the power factor falls with an increased charge.*"

In searching for the cause of this, we must go back to the causes affecting the power factor. For this purpose we again reproduce the vector diagram originally shown as Fig. 30 in

Chapter IV. We see that the size of the angle $\phi$ depends on the resistance of the bath $r$ and again upon the factors $m$ and $L$. In our examples, in both of which the periodicity remains the same, the factor $m$, depending upon the latter, also remains unchanged. Therefore, only $r$ and $L$ remain as means for reducing the power factor.

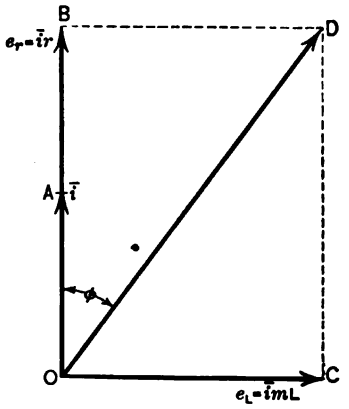



FIG. 78.

It is evident from the diagram that when the resistance $r$ of the bath is reduced the angle $\phi$ becomes larger and the power factor, or cos $\phi$, consequently decreases. If the length of channel remains the same, but the cross-section of the bath changes, the resistance will change, because $r = \rho \frac{l}{q}$ and as the example showed, that raising the charge from 1350 kg. (about 3000 lb.) to 1800 kg. (about 4000 lb.), that is about 33%; and as the cross-section of the bath increased in like ratio, it becomes apparent why it is that the power factor falls with an increasing metal charge in the bath.

Beside the resistance of the bath, however, the coefficient of self-induction has a noteworthy influence on the size of the power factor. It was shown in Chapter IV that the coefficient of self-induction depends upon the form and arrangement of the conductors. In order to give the reader an idea of this influence, it may be said that for conductors of ring form having a circular cross-section, the following formula for the coefficient of self-induction holds good:

$$L = \frac{\pi D}{2} . (4 \log \text{nat} \frac{8 D}{d} - 8) . 10^{-9} .$$

Here $D$ denotes the diameter of the wire coil, and $d$ the diameter of the wire itself.

This formula, however, is only strictly correct provided the conductor is not in the vicinity of any good magnetic conductors.

However, it follows that the coefficient of self-induction primarily depends on the surface surrounded by the ring formed conductor, and that the coefficient of self-induction increases, the larger the surface becomes. Besides this the cross-section of the conductor also influences this factor, and as the formula shows, the coefficient of self-induction becomes a little better with increasing cross-sections of the conductor. This latter influence, however, is too small to nullify the lowering of the power factor, occasioned by the lowered bath resistance when the cross-section of the bath is increased. The proof of this is plainly seen by the examples given.

From what has just been said relative to the power factor it is apparent what the active causes are, and why Kjellin and similar furnaces had to be built with ever decreasing periodicities, for increasing capacities. We have just seen, that the power factor decreases when the charge is increased, due to the lesser resistance to the bath. As we saw in Chapter IV, the lowering of the power factor necessitates a greater current flow than it would have at a higher power factor, in case the furnace is to receive the same power, at a lower power factor and at the same voltage. Heavier currents, however, demand an increase in the copper cross-section of the primary winding, which in turn increases the needed space for winding the coil. To this must be added that with an increased capacity the energy absorbed by the furnace is naturally greater, so that the processes to be followed may not be unnecessarily expensive. This, too, necessitates the use of a larger copper conductor, and consequently further increases the winding space. With the same thickness of the furnace refractories, this can only take place, however, when the diameter of the ring shaped hearth is increased; and, as we saw before, this causes a larger coefficient of self-induction, and with it a further decrease in the power factor. With an increasing charge, therefore, the power factor would drop very fast, and this would very quickly lead to impossible operating conditions with the frequency remaining the same. Fortunately by lowering the frequency, we have a means for meeting the lowering power factor. In order to recognize this, if we refer

to Fig. 78 again, we see that the power factor is determined by the equation—

$$\cos \phi = \frac{r}{m L}$$

as $r$ and $L$ are given by the bath conditions, it is only possible to influence the power factor by altering $m$, and the power factor will, of course, be larger, and so much better, the smaller the quantity $m$. This quantity $m$ is determined by the equation $m = 2 \pi \nu$ where $\nu$ equals the number of cycles per second. By

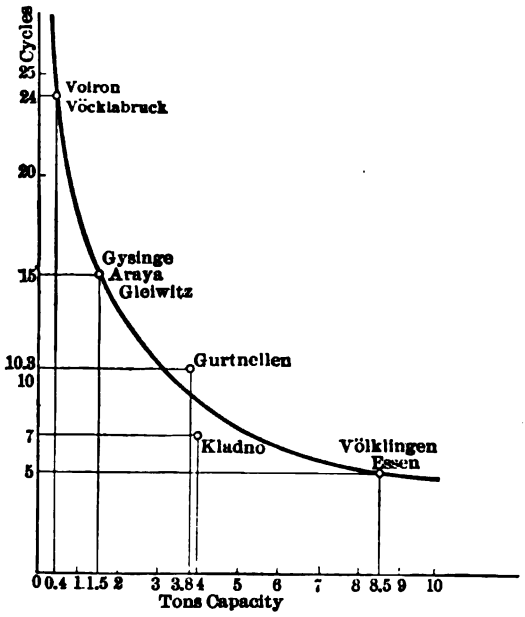



FIG. 79.

lowering the periodicity, the quantity $m$ is reduced, and hence the value of the power factor is kept within reasonable limits for any particular size of furnace. Kjellin also availed himself of this means, and the curve shown by Fig. 79, which appeared in the *Elektrotechnische Zeitschrift*, in 1907, in an article by Englehardt, shows under what conditions the lowering of the frequency is desirable, with Kjellin furnaces of increasing

size actually built and operated. The conditions here described are also, of course, more or less applicable for every other induction furnace having a channel hearth.

It is well to mention that the *lowering of the periodicity* is not always feasible as the normal frequencies are 25, 50 or 60. It is not possible to change from one frequency to another by means of stationary transformers, in the manner employed for voltage transformations. If it is desired, therefore, to connect to an existing power station having a higher frequency than would be favorable for the furnace operation, it will be necessary to employ a rotary transformer. In addition a low power factor necessitates comparatively large iron cross-sections in the generator as well as in the transformer, and consequently greater copper lengths for the windings, making a more expensive installation. In order to give an idea of this, we may say that a generator of 25 cycles only costs half as much as one of equal capacity of five cycles.

As electrodes are avoided with Kjellin and other induction furnaces, the regulating apparatus for the carbon electrodes themselves is not needed, so that the furnace does not require any movable parts, except the covers. With the absence of electrodes there are consequently no electrode losses, which leads us to the *efficiency* of the Kjellin furnace. As the furnace is merely a specially designed transformer, the only losses occurring are the ones usually prevalent in ordinary transformers. These losses are due to the iron losses, which are caused by the continually changing direction of the magnetization, and the copper losses in the windings. As the secondary winding in Kjellin furnaces is solely composed of the metal in the hearth, all the losses which ordinarily appear here, are used instead to advantage, because all electrical losses manifest themselves as heat, and in this case the generation of heat is what is desired. Losses, therefore, can only occur in the iron core and in the primary coils. The purely electrical losses of the induction furnace transformer hardly exceed those of the ordinary transformer. On the whole, the electrical efficiency of the induction furnace is the best obtainable in any electric furnace. As a

proof of the highest efficiency of induction furnaces, it may be said that, the most frictionless transposition of electric energy imaginable into heat takes place here, as the current generated in the secondary circuit, *i.e.*, the induced currents in the iron bath, are generated at their point of origin and directly changed into heat.

Induction furnaces may, therefore, be built for any existing voltage, for to generate the particularly high current in the bath is only dependent on a suitable number of turns in the primary winding. It was pointed out, for example, that the furnace at Gysinge, having a capacity of about 1500 kg. (3300

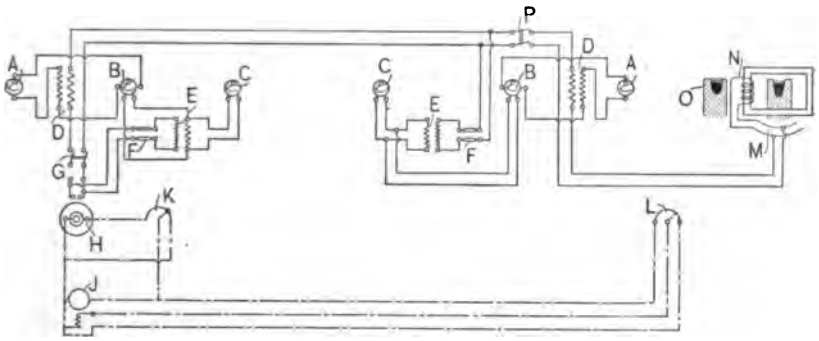



FIG. 80.

lb.), is operated at 3000 volts, its primary coil is arranged with 295 turns, so that we have a secondary voltage corresponding to $\frac{3000}{295}$ or about 10 volts. As it is possible to use any existing high potential current on the primary side, it is necessary that this part be shielded against coming into any possible contact with other conducting material. This is accomplished by completely encasing the furnace transformer, *i.e.*, the transformer is built with a protecting shell, so that contact with any dangerous parts during the operation of the furnace is practically impossible. In addition to this the protective covering is connected with a copper conductor to the earth, or grounded—so that in case any high potential current should strike the protective shield, it would immediately become harmless and flow to earth. Hence

all danger to those operating the furnace is eliminated, and the best proof of the absolutely safe operation of the furnace, is the fact that thus far no operatives of induction furnaces have been injured.

As the operation of the induction furnace is usually not easily understood for non-electricians, the schematic connections of a Kjellin Induction furnace installation are shown in Fig. 80. In this figure the left half shows the electric installation at the central station, and the other side the actual furnace installation. The heavy lines between the central station and the furnace indicate the main high potential conductors. This high tension current is measured with instruments, by interposing so-called potential and current transformers between them and the main conductors so that the instruments only carry low voltage currents. The thin full lines indicate the necessary wiring for this. If we neglect for the moment the dotted lines, we see that the full lines of the circuit in the central station as well as at the furnace show instruments at either place, consisting of an ammeter *A*, a wattmeter *B*, and a voltmeter *C*, which must be watched during the operation of the furnace. *D* indicates the current transformers for measuring current, and *E* the potential transformers for measuring the voltage. In order to protect the instruments, the fuses *F* are inserted, whereas *G* represents an automatic release, which cuts out the main current when it is overloaded and thereby protects the generator. The generator itself is shown by *H*. At the furnace we see *M* which designates the sectors on which copper brushes rub, (similarly to those usually used on a motor,) in order that the furnace may receive its current and still remain in its tilted position. From the contact rails, the current is carried to the primary winding *N*, in well insulated conductors, which generate the induced currents in the channel *O*, whose contents simultaneously act as the secondary winding. If we also mention the switch *P*, at the furnace, which permits the current to be interrupted there, we have referred to all the apparatus of the operating circuit.

Of great importance is the regulating apparatus of an electric

furnace, which permits the furnace to receive much or little energy, and thereby enables the furnace to be operated practically. We saw previously with arc furnaces, that besides this apparatus, automatic regulators were also necessary, in order to smooth out the current fluctuations occasioned by the action of electrodes, and to keep a predetermined and constant amount of energy at the furnace. These regulators are wholly absent with induction furnaces, as sudden power fluctuations with induction furnaces are absolutely precluded. We have, therefore, only to confine ourselves to the apparatus which is necessary to regulate the incoming energy, and for this it is quite sufficient to alter the primary voltage of the furnace.

In order to easily change the voltage during the operation at any time, a handwheel rheostat, or regulator is placed at the central station, as well as at the furnace, by the aid of which the magnetizing or exciting current is varied at the alternator. In Fig. 80, $J$ represents the exciter generator, the heavier dotted lines indicate the main wiring of the excitation circuit, and the lighter dotted line denotes the shunt circuit of the exciter generator or exciter. At the furnace is the small regulator $L$, by the aid of which the field of the exciter is regulated with a very light current, whereas the regulating resistance $K$ enables the main current of the exciter to be changed. In this way it is possible to regulate the voltage at the central station as well as at the furnace, and in order to keep both regulating platforms in communication with each other, it is usual to have them connected by means of loud-speaking telephones.

After this discussion of typical Kjellin furnace switching methods, which are applicable also to other induction furnaces having special generators, we may turn to the *comparison* of the Kjellin furnace with the ideal furnace. That the Kjellin furnace requires special generators more than any other furnace discussed in detail, was seen when discussing the influence of the power factor; this is the reason for the abnormal frequencies, which, up till now, have been necessary for all induction furnaces having only the ring-shaped hearth. The operation of a Kjellin furnace with other than its own special generator, is not

practicable and this increases the installation cost, and affects the obvious advantages of the furnace.

Among the special advantages of the Kjellin furnace, as the typical representative of the pure induction furnaces, we may count first of all the absolute avoidance of any sudden or undesirable *power fluctuations*, which must be classified as unavoidable with arc furnaces having vertical or inclined electrodes. That there are no reasons for these sudden power changes with Kjellin furnaces we see when we realize, that with this pure resistance heating, sudden power changes could only

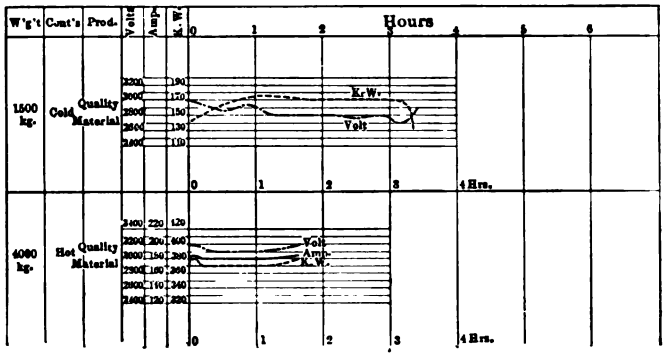



FIG. 81.

occur, with sudden heavy cross-sectional changes of the bath. This condition, though, is positively eliminated because the cross-section can only vary when charging or when tapping the furnace, and as these operations are always the function of a greater or lesser amount of time, it is evident that cross-sectional changes can only appear gradually during this time, and likewise the resistance changes and changes the current strength. This is proved from the operation of all induction furnaces. There is, however, a decided advantage in avoiding any sudden power changes, for it is evident that the generator required for an induction furnace needs to be just large enough to carry the maximum load required over a period of time; whereas a generator for an arc furnace would have to be more liberally proportioned, considering the heavy load fluctuations. The curve

of Fig. 57 shows to what degree these power fluctuations occur, and it is interesting to compare this with the one shown by Fig. 81, which latter shows a Kjellin furnace under various methods of operation. These conditions naturally tend to cheapen the construction of the generator for the induction furnace, so that the greater cost occasioned by the generator of abnormal periodicity is at least compensated for to a certain extent.

It was seen when discussing the switching mechanism, that the regulation of the incoming energy of a Kjellin furnace is accomplished in the simplest way imaginable. It may, therefore, be well to point out again that the regulation of the energy of an induction furnace is accomplished in the most ideal way. For with an electric furnace, the same temperature is found throughout the whole bath, so that any change of the incoming energy alters its temperature gradually without in any way causing any overheating at any one spot, which is always to be dreaded under the electrode in arc furnaces.

It has also been mentioned that the induction furnace undoubtedly has the best attainable *electrical efficiency* of any electric furnace, because all electrode losses are avoided, and hence only the transformer losses come into play with induction furnaces, except when a special generator is used, and then only the primary copper losses and iron losses appear in the transformer parts built into the furnace. Transformer losses are, however, present with nearly every arc furnace, thus a transformer is almost invariably erected as closely as possible to the furnace.

As the Kjellin furnace today is always built of the *tilting* variety, it fulfills one more demand of the ideal electric steel furnace. On the other hand, the Kjellin furnace cannot fulfill the demand which provides for *an easily surveyed and accessible hearth* and herein lies its great weakness as compared with other furnaces; its use is therefore restricted to that comparatively small field, in which the requirement of an easily surveyed and accessible hearth is immaterial. Such occasions may, however, occur where a furnace is intended to be a substitute for the crucible furnace, in which a very pure material is mixed in the

bath, or in case the charge from other furnaces is merely to stand in the electric. The Kjellin furnace or any other induction furnace with a ring-shaped hearth, is found preferable to be used in this way. The advantage it has over the crucible, is that much larger homogeneous quantities of a desired quality can be obtained, whereas crucibles always have a very limited capacity; it is, difficult therefore, to produce large amounts of a predetermined and regular composition. Furthermore, the induction only needs a very limited number of operating men.

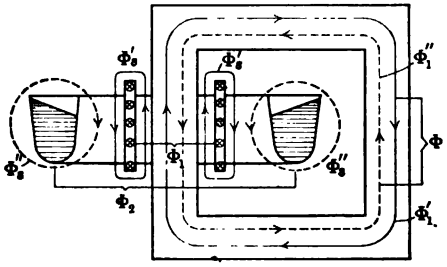


FIG. 82.

Finally, a considerable amount of money can be saved in the crucibles (from $5 to $8 in regenerative furnaces, but as high as $20 a ton in non-regenerative "pan system" oil burning furnaces). As a substitute for the above, the Kjellin furnace seems admirably suited. For most other classes of work, however, the furnace is unsuitable; because it is practically impossible to thoroughly remove the slag from the ring-shaped channel hearth, and thus avoid affecting the purifying process for the succeeding slag. This fact has been proved in practical work by many and extensive tests.

One of the next requirements of an ideal furnace is the *adequate circulation of the bath* by the aid of which the furnace will produce a thoroughly regular material. On account of the magnetic conditions of the Kjellin furnace the circulation of the hearth metal is almost perfect. The proof of this was first published by *Englehardt* in *The Electrotechnische Zeitschrift*, in 1907, and is shown schematically in Fig. 82. Here $\phi_1'$ denotes

the lines of force generated by the primary coil, which take their path through the transformer iron. $\phi_1''$ denotes those which are generated by the secondary winding or the bath, and take a path through the transformer iron in the opposite direction, so that we have resultant lines of force, denoted by $\phi$. On account of the large distance, however, between the primary and secondary coils, there must also necessarily be a number of stray lines of force, which find their path through the air. As far as these are generated by the primary winding, they are designated by $\phi_s'$, and when generated by the currents flowing in the iron bath, they are designated by $\phi_s''$. These lines of force play a very important part, as the iron and the molten metal offer a much lesser resistance to the lines of force than the air does, so that it may be assumed that a part of the secondary lines of force find their way through the molten metal. Both lines of force, $\phi_s'$ and $\phi_s''$, therefore, essentially flow in opposite directions, as they are generated by currents having opposite directions. (We saw in Chapter IV that the induced current, *i.e.*, the current generated by induction, is always in the opposite direction to the primary current, which is the case here.) Fig. 82, however, shows that the opposite direction of these two lines of force circuits, makes the direction of current flow the same between the primary winding and the bath. It is a fact that lines of force of the same direction repel each other, hence forces must appear between the primary winding and the bath, which endeavor to repel the molten metal from the primary coil toward the outside. In Fig. 83 this force is denoted by $P_s$. Besides this the force of gravity also operates on the bath. Both forces work at right angles to each other, causing a resultant force. Accordingly the surface of the bath inclines at right angles to this resultant, as is shown in Fig. 83.

As a matter of fact the inclination of the bath surface can be more or less plainly seen with all Kjellin furnaces.[1] The flow of the metal is from the outside upper edge towards the inner lower one, which in this way provides an intimate mixing of the metal

[1] The inclination of the bath of an 8-ton Kjellin furnace is about 24° (See *Stahl und Eisen*, 1910, p. 1071).

in the bath. One explanation of this flowing or rolling of the bath may be made, if we assume that the parts lying on the outer upper edge are subject to a greater cooling than the inside lower lying metal, so that the higher lying, cooler and consequently specifically heavier metal portions will tend to sink to the bottom, whereas the hot portions will rise.

The circulation described has the advantage of the most thorough mixing of the whole furnace contents without mechanical aid. With large Kjellin furnaces operating at low frequencies, however, it has frequently happened that the inner wall of the

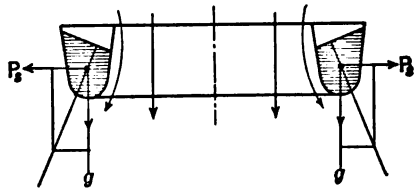


FIG. 83.

refractories is quickly destroyed by the circulation directed against it. It was only after decided efforts on the part of the *Poldihütte* at Kladno, Austria, in applying the refractories in a special way that they were able to withstand these attacks, so that the lining, even with an 8-ton Kjellin furnace, now lasts six weeks, (164 heats,) when melting cold stock,[1] and 494 heats with hot charges.

In the discussion of the Kjellin furnace circulation, it must be stated that the pinch effect mentioned in Chapter III does not come into play as long as the furnace is used for melting iron because the bath cross-sections in relation to the current density are too large when this furnace is thus used. The pinch effect could only be found if the cross-section should be especially narrowed at particular places.

If it has been shown that the Kjellin furnace is only a substitute for the crucible, still it may be said concerning the sizes this furnace has attained, that at present the Kjellin furnace

[1] See also *Iron Age*, Nov. 30, 1911, when refining hot metal.

has a capacity of 8 tons of steel. One of these furnaces is operating successfully at the works of Friedr. Krupp, at Essen, Germany. Fig. 84 shows the transformer of one of these 8-ton Kjellin furnaces for only five cycles. It is hardly advisable to build Kjellin furnaces of a larger size than this, first because the fre-

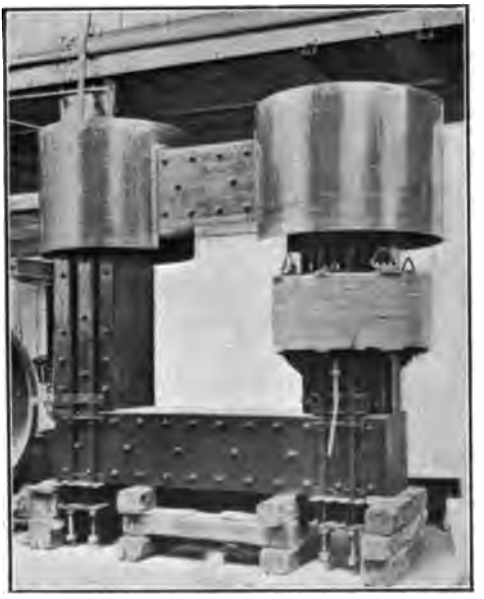


FIG. 84.

quency would have to be reduced still further, and secondly, because it is to be feared that there would be difficulties with the durability of the refractories.

Regarding the *total efficiency* of the furnace, we append the following:

Several reports have been made by Englehardt on the Kjellin furnaces. In *Stahl und Eisen*, 1905, page 205, where he speaks of melting a charge consisting of 1/3 pig iron and 2/3 scrap, he figured with a theoretical power consumption of 489 Kw. hours per ton. If we compare the results obtained with the 1.5-ton Kjellin furnace, where with a mixture as above it took

966 Kw. hours to melt a ton of steel over a six-hour melting period, and 800 Kw. hours during a four-hour period, this gives a total efficiency of 50% for the six-hour melting time, whereas Kjellin himself mentions 47%, and an efficiency of 60% for the four-hour melt. It is interesting to observe how the shortened melting time raises the attainable efficiency of a furnace. The reason for this is that on one hand, the radiation losses are prolonged for six hours, whereas on the other they only occur for four hours. While melting, therefore, it is advisable to operate with as high an incoming energy as possible, and to hasten the work to the greatest extent. The 60% efficiency with a four-hour charge is to be considered as most favorable, considering the small size of the furnace (1½ tons). The attainment of such efficiencies, with Kjellin furnaces having such an unfavorable hearth, as far as radiation losses are concerned, is only possible because the electrical losses are at a minimum. In spite, however, of the assumed greater radiation losses of the Kjellin furnace as compared with the arc furnace, we find that the induction furnace always has a higher total efficiency than the arc furnace. This becomes even more apparent with larger furnaces. In the same article as above, Englehardt gives an efficiency of an 8-ton furnace corresponding to a power consumption of 590 Kw. hrs., when melting cold stock. This gives a total efficiency of about 80%. That this figure is attainable as a matter of fact is best proven by the practical operation, where with this ring-shaped hearth a power consumption of only 580 Kw. hrs. per ton of steel was attained by the use of suitable heat insulating covers.

Regarding the *application* of this furnace, we refer to the statistics in the closing chapter.

The sale of and giving licenses for Kjellin furnaces is handled by the Gesellschaft für Elektrostahlanlagen in Berlin; in England and her colonies, except Canada, by the Gröndal-Kjellin Co., London, and in the United States and Canada formerly by the American Electric Furnace Co., New York, and at present by Siemens and Halske A— G—, New York.

# CHAPTER XII

## THE RÖCHLING-RODENHAUSER FURNACE

ALTHOUGH we saw in the previous chapter that the Kjellin furnace and the induction furnace having a ring-shaped hearth, are inapplicable for many uses, and hence at a great disadvantage with the arc furnace, still the induction furnace has important advantages which must not be overlooked, especially where this furnace in its original form finds its best field; *viz.:* in the replacement of the crucible furnace. These advantages include the absence of electrodes, and consequent saving in operating costs and also the avoidance of the risk of accidental impurities from the electrodes contaminating the bath, which latter is especially feared when making tool steel. The electrical efficiency attainable is also much higher. The absolutely steady furnace operation is almost ideal, and this steadiness is equally excellent for the central station. Finally, we may regard the uniform heating effect throughout the entire bath of the induction furnace together with its strong circulation, an advantage over the arc furnace, even though the experience thus far gained concerning the influence of the high temperature of the arc on the quality of the steel is not yet extensive enough to form a conclusive opinion on this point.

Realizing the good points of the induction furnace referred to above, it was not long before efforts were made to retain the advantages of induction heating. For the disadvantages of the single ring hearth were clearly recognized. Later on pains were taken to alter the hearth in such a way that it would meet the demands of the metallurgist, and to produce thereby an induction furnace which would be equal to any refining work. It was recognized that if at the same time the operating conditions could be bettered (these as we have seen with the Kjellin furnace

necessitate the use of machines having unusual periodicities), then the induction furnace would be able to enter into successful competition with the arc furnace in any field.

It was these considerations which led the Röchling Eisen und Stahlwerke at Völklingen on the Saar, Germany, to consider the problem of re-designing the induction furnace. This decision was reached only after it was clearly recognized that the single-ring channel induction furnace was not practical for refining work.

The first German Röchling-Rodenhauser patent was applied for on May 6, 1906, and subsequently granted (No. 199354[1]).

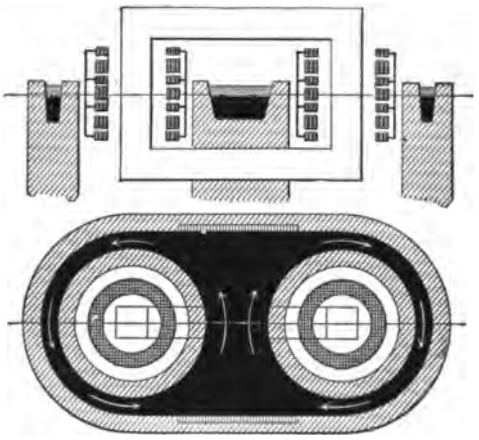


FIG. 85.

This patent covers an induction furnace as shown schematically in Fig. 85. It may be seen that both cores of the transformer are provided with coils, in contradistinction to the Kjellin construction. Both cores are surrounded by an induction channel, which are joined between the cores in the middle, forming a roomy working hearth. This middle section is heated by means of an auxiliary current supplied by a secondary winding wound next to the primary winding, which has the marked advantage of reducing the stray field, and hence improves the power factor.

[1] Corresponding to U. S. patent No. 877739 of Jan. 28, 1908.

The furnace principal shown in the sketch is known as the Röchling-Rodenhauser furnace. This furnace was investigated for its usefulness at the Röchling Iron & Steel Works from July to September, 1906, by means of a small test furnace holding 60 kg. (132 lb.), and operated from a 50 cycle circuit. Fig. 86 shows this furnace at one stage of the tests with suspended electrodes composed partly of conductors of the second class, being used as a mode of utilizing the auxiliary current, notwithstanding

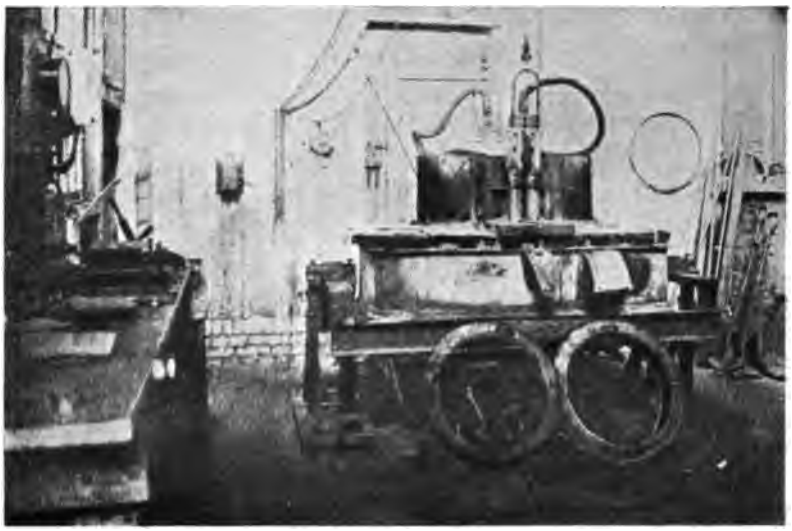


FIG. 86.

that the patent specification mentions conductors of the second class for transferring the current, which is the method exclusively employed today.

The tests with the small furnace were later continued with a somewhat larger furnace, holding about 300 kg. (660 lb.).

In the course of the development a furnace of about 500 to 750 kg. (1100 to 1650 lb.), was ordered by and constructed for the *Eicher Hüttenverein*, which company was desirous also of investigating this form of furnace, knowing of the tests carried out at Völklingen. Until this time, the small furnaces were

provided with covers which had to be lifted when charging, but the Eicher Hüttenverein furnace was the first one to be supplied with doors, thus simplifying the furnace operation. This arrangement may, at the same time, serve to indicate how, with the progress of developments, the work of refining in the furnace was transferred more and more from the channels to the main hearth, where it is carried on today exclusively, the channels serving only as heat carriers, without in any way accomplishing any metallurgical work.

One of the determining factors in the further development of the furnace was due to the erection in the spring of 1907, at Völklingen, of an 8-ton Kjellin furnace which operated at only five cycles. The exhaustive tests carried on with the aid of this furnace, furnished convincing proof that the ring-shaped hearth was unsuitable for extensive refining, which was the goal of the Röchling Iron & Steel Works. On the other hand, these small test furnaces, above mentioned, gave the most favorable results in the refining of steel. Because of this a Röchling-Rodenhauser furnace was built and designed for the electric plant which had been installed to operate the five-cycle Kjellin furnace. This first large furnace had a capacity of about 3 tons and was placed in operation on June 22, 1907. It soon demonstrated the advantages of the new furnace principle for large units.

In order, however, to render this furnace system adaptable to all conditions, there was still one further step to take, *i.e.*, to derive means to operate the furnace with polyphase current. For as long as it was not possible to use polyphase current directly in the induction furnace, the advantage of the induction furnace in its being able to be operated with any voltage that is available, would be of minor importance. The reason for this being that as it is only possible to operate the furnace with single phase current, it follows that the installation of a rotary transformer would be necessary when obtaining power from a three-phase circuit.

As early as 1907, therefore, the constructive features of a polyphase furnace were considered, and in February, 1908, the first polyphase Röchling-Rodenhauser furnace was placed in

operation. This was designed for 50 cycles and connected to the 3 phase electric plant of the Röchling Iron & Steel Works. The application of the furnace to polyphase current was patented in all industrial countries.

These short remarks show the development of the Röchling-Rodenhauser furnace, which can be obtained to-day not only for single phase current, but also for two and three phase current, for any convenient voltage and for normal frequencies.

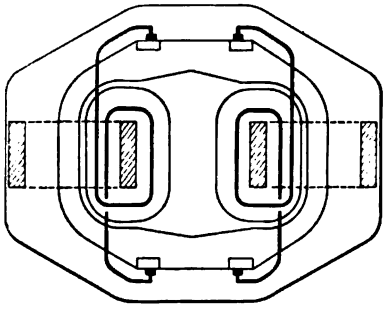


FIG. 86a.—Two Phase R.-R. Induction Furnace.

In its present form the Röchling - Rodenhauser furnace consists of a casing of strong sheet iron, which is supported by means of a semi-circular saddle and rack on rollers, thus allowing the furnace to tilt. The tilting may be accomplished in any way desired, but is usually done by means of an electric motor and suitable gearing.

The furnace transformer is built into the shell. The upper yoke of the transformer is arranged to be easily removable, while the lower yoke and the cores are securely fastened by bolts, to the furnace casing, so that the transformer may stay securely in position even though the furnace is tilted 45°. If we now turn to the furnace in its single phase form as shown in Figs. 87 to 89, which indicates a 5-ton furnace operating at 15 cycles, 5000 volts, we find two cores of somewhat long-drawn-out rectangular form. The cores are composed of a number of sections, which in turn are built up of paper-covered sheet iron of .3 mm. (.012 inch) thickness, the sections being separated from each other by the ventilating ducts *H*. Each core carries a primary winding *A*, and a secondary winding *B*. The primary winding is connected directly to the incoming voltage intended for the furnace, in the foregoing case, 5000 volts. The current is led to the windings by means of the usual high tension underground cable and thence

to brushes, by the aid of which it is carried to a copper slip ring. The current is then led directly to the winding, by stationary conductors carried on high tension insulators. These methods of leading the current to the windings have the advantage that the heating may be continued, for instance, when the slag is being rabbled off, *i.e.*, the furnace continues to receive its heat when in the tilted position. The secondary winding lies next to and

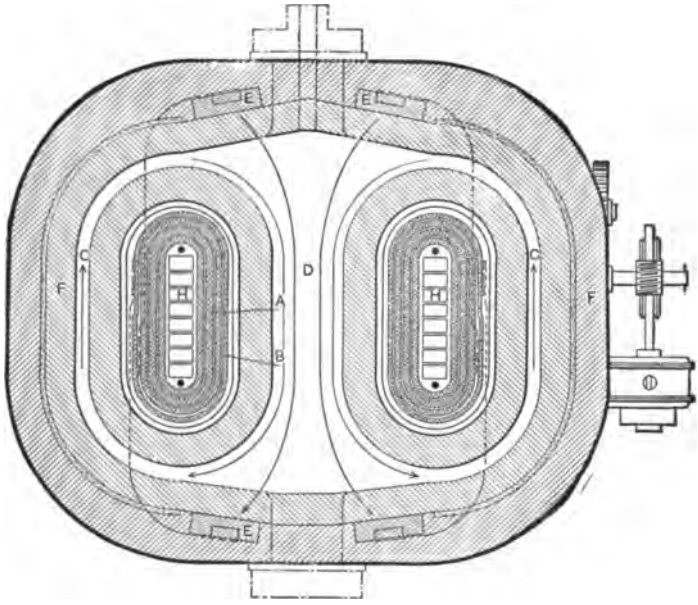



FIG. 87.

separated from the primary winding by an air space, which is both an insulating protection and a cooling chamber. The secondary winding is composed of heavy copper strips and carries very heavy currents at very low voltages. From this secondary winding, copper connections lead upwards from which the current is led to the poleplates *E*. These connecting pieces are represented by lines in Fig. 87.

The whole winding arrangement is surrounded by two cylinders of copper, brass or monel metal, which are separated from each other by an air space. Similarly there is an air space

between the secondary winding and the inner cylinder. The inner cylinder is closed at the top by means of dust catchers in such a way, however, that the cooling air from the furnace transformer may escape at the upper end with the least resistance. The method of supplying the cooling air is shown by means of the central air duct in Fig. 88, and the air direction is shown by the arrows. As a matter of fact this represents the method of

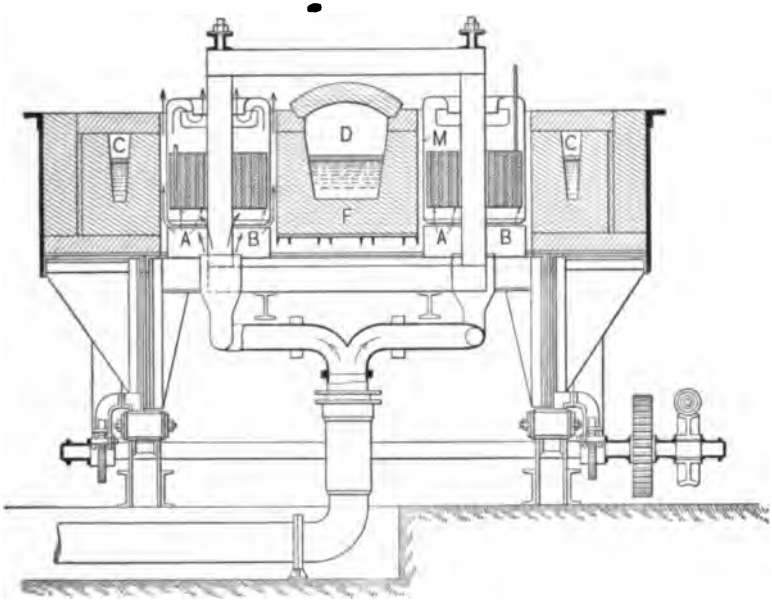



FIG. 88.

applying the air supply for Röchling-Rodenhauser furnaces today, for such a centrally located movable duct underneath the furnace is provided from which the air is led to both cores. The air is so divided that the greater part takes its path upward through the winding space, thereby cooling the coils and the transformer cores, whereas a smaller part passes through the space between the two protective cylinders *M*, in order to keep the heat radiating from the brickwork, away from the whole transformer construction.

Air is alone used for cooling from a blower usually of very

low pressure. At Völklingen for instance with an 8-ton single phase furnace the blower pressure only corresponds to 40 mm. (1.6 inches) water gauge pressure. These cooling arrangements have given the most complete safety to the furnace during the past 4 years' continuous operation.

In order that the unavoidable cooling of the furnace transformer may not cause too great heating losses, much considera-

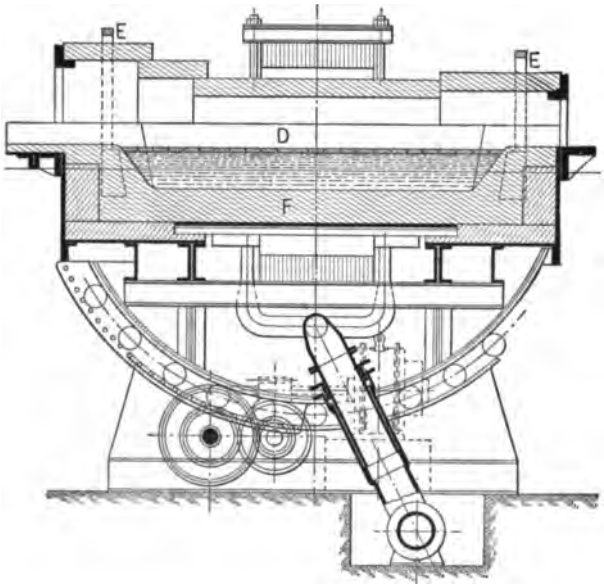



FIG. 89.

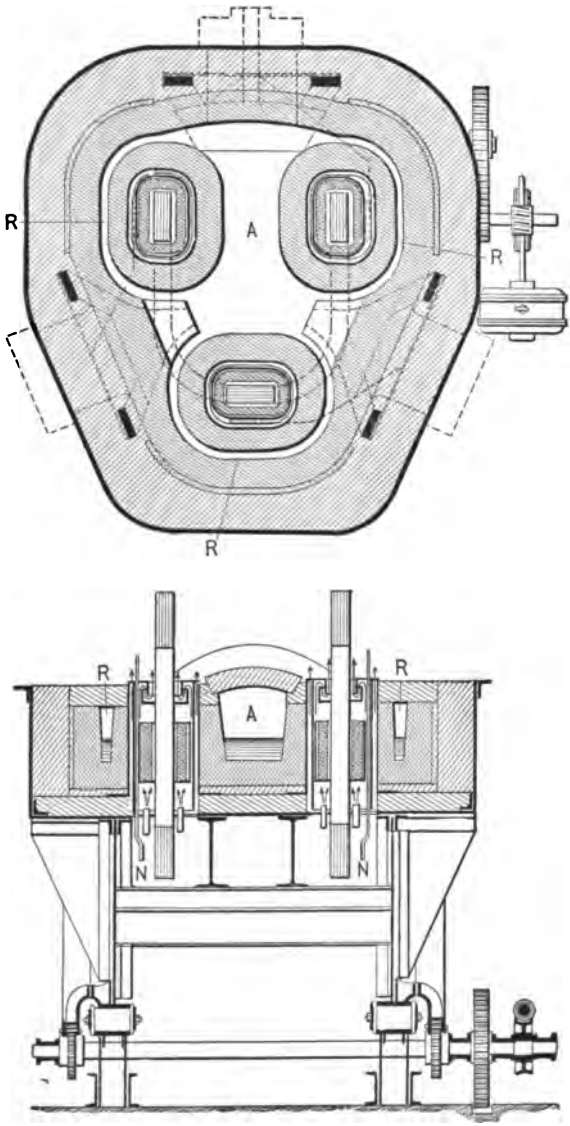
tion was given to the best possible heat protection for the hearth. On that account the outer protective cylinders are surrounded with a layer of granular material, which acts as a heat protector. On the outside of this follows the real refractory mass of either dolomite and tar or magnesite and tar. In order to obtain a hearth of the desired shape as shown in the figure, a wooden or cast iron templet is lowered into the furnace after the bottom has been rammed in, in a similar manner as with the Kjellin furnace. On the side of this templet, the hearth walls are tamped in, which when the templet has been removed leaves

the necessary space for the molten metal. The cross-section *a b* of Fig. 87 plainly shows that the hearth really has the shape of an 8. It may be seen that the transformer cores are surrounded on the outside by the narrow channels *C*, while between the cores lies the true hearth and working chamber. Working doors are provided at both ends of the hearth, which makes this easily accessible and hence greatly lessens the necessary attendance at the furnace, as the entire roof of the furnace covering both hearth and channels remains stationary throughout the whole working period. The channels themselves are not intended for the metallurgical process, but they are of course necessary to provide the induced heating currents for the hearth.

Concerning the hearth refractories, it may be mentioned that following the dolomite and tar outer hearth walls, there is provided a layer of coarse-grained heat insulating material, and that finally between this and the furnace shell is placed a ring of heat protecting brickwork. All parts of the roof covering are easily removable, in order that they may be easily lifted off and quickly replaced, in case a new lining is to be rammed in.

It was remarked before that the copper secondary winding *B* leads to the poleplates *E*. These plates are imbedded in the lining, as shown in Figs. 87 and 89. They are made of soft cast steel, and have the largest possible surface on the side toward the hearth. Between the poleplates and the bath is the hearth wall, which as we have seen consists of dolomite and tar, so that the poleplate is protected against direct contact with the molten metal.

Mention has been made in previous chapters that the refractories used are conductors of the second class. That is to say, these materials, which are non-conductors at low temperatures, lose their resistance more and more with increasing temperatures, until finally they become comparatively good conductors at the temperatures which are prevalent in electric furnaces. This property of conductors of the second class is utilized in Röchling-Rodenhauser furnaces to carry the current from the secondary winding by means of the poleplates to the molten bath itself. In this manner that portion of the lining




FIGS. 90 and 91.

over the poleplate may be designated as the mass which transfers or conducts the current.

At the beginning of the furnace heating this mass will act as a large resistance in the secondary circuit. This holds true as long as the furnace is heated up with iron rings, exactly as is done with Kjellin furnaces, and the same conditions exist when the furnace is charged with its first hot metal, so that at first we only have simple induction heating. As the furnace is further heated, the temperature also rises in the conductor of

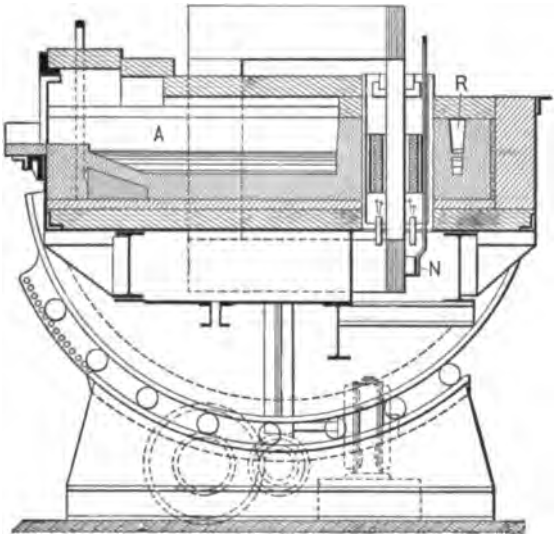



FIG. 92.

the second class in front of the poleplate, and the resistance consequently drops under correct conditions, the secondary winding soon carries a considerable portion of the total energy of the furnace to the bath. With the 8-ton furnace at Völklingen, this result usually takes place in twelve hours.

For the normal operation of the furnace there is therefore a double heating; first, we have the single induction heating in which case the ring formed parts of the hearth are to be designated as secondary circuits, and secondly the heating from

the current of the copper coil secondary winding, which is carried to the bath via the poleplates and conductive lining. The arrows in Fig. 87 show both current plates of the secondary side, which plainly show that the total current flows in the same direction through the hearth.

The conditions are much the same in three phase furnaces. These furnaces receive the three conductors from the three phase circuit on three cores, which are very similar to the ones of the single phase furnace, in that each core carries a primary and a secondary winding. Here also we find the coils surrounded with an inner and outer protecting cylinder, through which the ventilating air flows. In building these furnaces, it was the endeavor, of course, to provide a single roomy hearth, which could be easily surveyed and be easily accessible. Following these maxims the designs shown by Figs. 90 to 92 were evolved. The central hearth is consequently surrounded on three sides by the cores. Toward the outside, (corresponding to the arrangement of the single phase furnace,) these are encompassed about by induction channels, which join together and form the central hearth *A*. The yoke is often bent around in the form of a horseshoe, by the aid of which the cores are connected at top and bottom.

In order to make the hearth easily accessible and visible a door is fitted between each two cores, of which the one opposite the central cores is supplied with the tapping spout. The furnace is therefore emptied in that direction. There is a poleplate having two arms near each door toward the bath, which is protected by the conductive lining from the bath, as in the single phase furnace. The arms of the poleplates are connected with one pole of the secondary copper winding, whereas the free ends of the other pole are connected together to the neutral point *N*, by means of the copper bar connections there shown.

In order that there shall be no misconception about the current connections of a Röchling-Rodenhauser furnace Fig. 93 is given which shows the schematic diagram of a single phase. Similarly Fig. 94 shows the schematic diagram of a three phase furnace.

In Fig. 93 both primary coils of the single phase furnace are shown connected in parallel. This also applies to the secondary coils, which are connected in parallel by the poleplates, between which the current flows through the bath. Fig. 94 shows the primary winding for a three phase furnace and their neutral point *N* 1. The heavier drawn secondary winding of the three cores has one end of each coil connected to the neutral point *N* 2, while the free ends are also here connected to the pole-

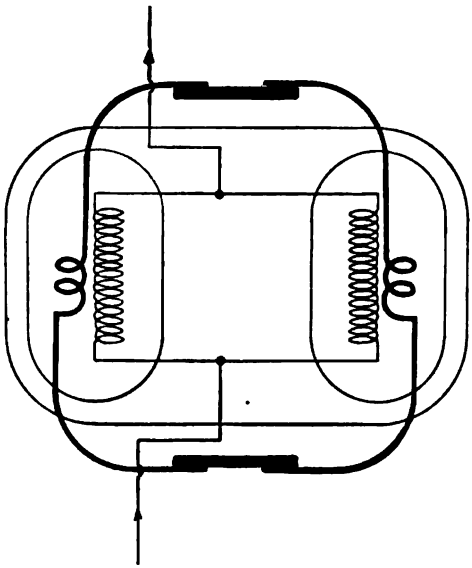


FIG. 93.

plates, between which the current-carrying lining and the bath are connected as heat-resisting material. Besides this both figures show the hearth and channel limits. The conduits of a channel and hearth form a short circuited secondary, in which the heating currents are directly induced.

The *operating method* resembles that of the open-hearth furnace, as a roomy working hearth is provided, and hence the conditions are present for successful refining work. If the furnaces are to be heated up, and hot metal is obtainable, this heating is accomplished similarly to the method used with

Kjellin furnaces, *i.e.*, iron rings for starting are laid in the furnace channels before the roof is replaced, which rings serve to bring the lining to a red heat under the action of the induced currents. When this is accomplished, hot metal is taken from any convenient melting furnace and charged in the electric furnace and with this charging the starting or heat rings are melted, which

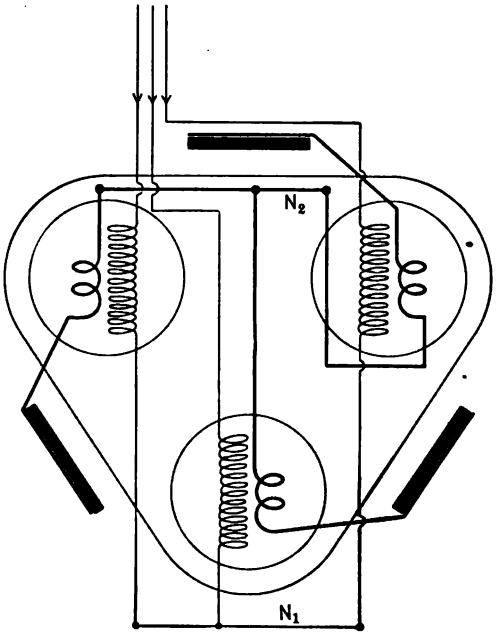



FIG. 94.

permits a quicker heating up of the furnace, as the cross-section is larger and consequently the energy supplied is greater. This heating permits the furnace to be placed in operation in the shortest time. It has, however, the disadvantage that it necessitates the use of molten metal from some other melting furnace. Such apparatus is often available and the molten metal may be obtained from converters, open-hearth furnaces, cupolas, crucible pots or even blast furnaces, so that the disadvantage is seldom felt. It is more difficult, when a source of molten metal is not available, to start the electric furnace. and a melting furnace

would therefore have to be furnished just for this purpose. In order to avoid this disadvantage, trials were made at the works of the Röchling Iron & Steel Co., with the object of starting up induction furnaces without the use of molten metal. This test produced satisfactory results, and the method is patented.

In accordance with this method, the starting rings are solidly packed with pieces of scrap, steel turnings, etc., until the heating channels and the hearth are completely filled. After the roof is replaced, the current is switched on, and the heating rings soon become red hot under the action of the current. This assumes that with the furnace voltage remaining the same, the absorption of energy will rise. With a 2-ton furnace it is possible, for instance, in twelve hours, to render the entire furnace contents fluid, and the normal operation may then start. When heating up with hot metal about eight hours would be necessary in order to proceed with the normal furnace operation.

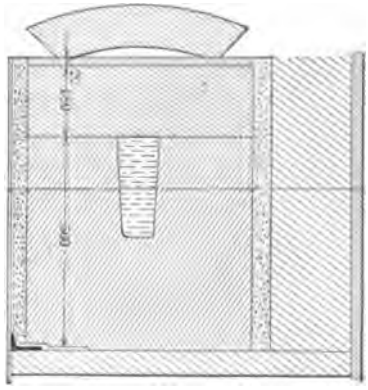


FIG. 95.

A normal heat with a Röchling-Rodenhauser furnace is much the same as with an arc furnace. The dephosphorizing usually occurs first, after which the slag is completely rabbled off, so that no deleterious material remains to delay the formation of the new slag for desulphurization. The removal of the slag occurs by rabbling through the doors. Of course it is impossible to remove the slag from the channels, where they surround the cores, as these channels are quite unsuitable for this work. On this account they are permanently closed in by the furnace roof, as is the hearth itself. As the slag cannot be removed from the channels some provision must be made so that the slag is prevented from entering the channels. This is

now accomplished by placing fire-resisting bricks of magnesite or dolomite across the commencement of the channels in such a way that the iron bath in the hearth is 1 or 2 cm. (3/8″ to ¾″) higher than the lower edge of the channel bridging bricks. In order to avoid as much as possible the heat losses occasioned by the bridging channel bricks coming into direct contact with the metal bath, a further normal roof of ordinary fire-brick is placed over them, which helps to lessen the heat losses by entraining a stationary layer of air. Fig. 95 shows these channel bridging bricks, together with the refractories surrounding the channel.

Mention should be made of the behavior of the Röchling-Rodenhauser furnaces when melting down scrap. So far it has not been possible to avoid the necessity of having in the furnace

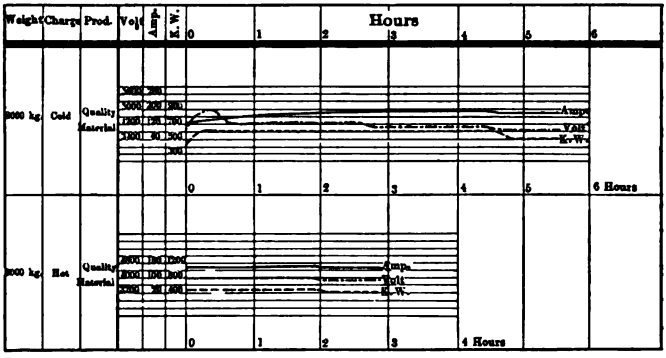



FIG. 96.

a portion of the charge, which, as we have seen with the Kjellin furnace also, is necessary when working up scrap, in order to provide the necessary circuit for the induced current, so that the scrap charged in the furnace may be melted down under the influence of the electric heating currents induced in the remaining portion of the previous charge. When scrap is to be melted down, therefore, and no fluid charge is at hand, the disadvantage consists in not being able to pour the entire charge. A certain percentage, say a quarter or a third of the entire contents, must remain in the furnace. The conditions are of course different when operating partly with a fluid charge, as for instance from

a converter or an open-hearth furnace and partly with scrap. Then the conditions are similar to working only with a hot charge, so that there is no reason for leaving any of the charge in the furnace. With a mixed charge, therefore, the metal is fully teemed after each heat, after which some fluid metal is taken from some other furnace and poured into the electric furnace, which permits of the flow of the induced current. Thereupon the metal to be melted is charged gradually or at once, to such a degree that the cold and hot furnace contents at times reaches the roof. After this no attention is necessary until the entire contents is melted down. This takes place without the slightest current disturbance, while the current and kilowatt curves rise slowly, as shown by the curves in Figs. 96 and 97, which

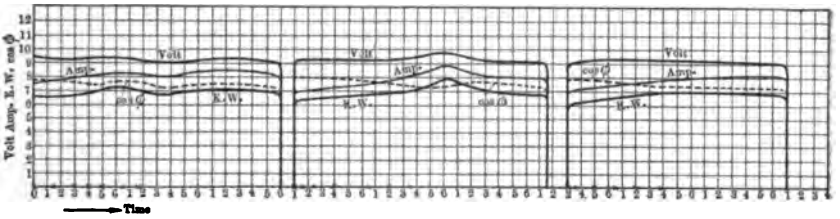



FIG. 97.

were taken from an 8-ton single phase furnace, and from a 1.5-ton three phase furnace, respectively, both at Völklingen. In the latter curve it is to be noticed that one division denotes 45 amperes, also 50 volts, also 30 kw., also .1 for the power factor, and ten minutes. The crosses on the bottom line denote that 100 kg. of scrap were charged.

It is also of importance from the standpoint of the practical operation of a furnace system that it is convenient to shut down the furnace for a limited time, for instance over Sunday. During such stops, a Röchling-Rodenhauser furnace is partly charged or even filled to capacity. It is then sealed up, after which the current is switched off and the furnace requires no further attention. When it is desired to start up again, the current is switched on for several hours, and the furnace is thus heated up anew.

When starting up in this way with the furnace fully charged, the 8-ton furnace at Völklingen after a 20-hour shut-down is ready for normal operation in about six hours.

The method of operation of the electric furnace is exactly the same as with the Kjellin furnace, as far as the induction heating is concerned, which is generated by means of the primary coil, in the ring-shaped portion of the iron bath. This is applied in Röchling-Rodenhauser furnaces, twice on single phase, twice on two phase, see Fig. 101a, and three times on three phase furnaces. This heating therefore does not require any further explanation. On the other hand it is different with the secondary circuit, which is composed of the copper winding wound directly over the primary coil. The current then flows through the pole-plates, the current-carrying lining, and the metallic bath.

The object of the secondary circuit is to raise the power factor, and to aid the heating of the furnace contents. It was seen that the low power factor of the Kjellin furnace, especially the low power factor of the larger sizes, led to the use of machines having very low frequencies, which materially increased the cost of installation. The reason for this decreasing power factor is found in the low bath resistance, together with the high coefficient of self induction, which was caused by the great distance between the coil and the bath. It was therefore necessary to investigate these causes, if the above-mentioned lowering of the power factor was to be avoided.

In order to increase the bath resistance the long rectangular form of core was chosen, in place of the more circular shape used with the Kjellin furnace. Furthermore, by placing the winding on two or three cores, it became possible to materially decrease the inner periphery of the induced part of the bath, as compared to that of the Kjellin furnace. This brought about substantial advantages, so that the power factor with Röchling-Rodenhauser furnaces stays much higher than with Kjellin furnaces having equal capacities and equal frequencies, even during the heating up period, *i.e.*, at a time when the poleplate circuits cannot yet do much work, because the current-carrying lining has too high a resistance. In order to further decrease the leakage as much

as possible, because of the comparatively large distance between the primary coil and the bath still remaining, use was made of electric conductors placed in the path of the stray lines of force. This expedient was mentioned when discussing induction furnaces in general.

The conductors of Röchling-Rodenhauser furnaces, which are placed in the path of the magnetic leakage lines, are used therefore as secondary copper coils, so that the currents produced by lowering the leakage field are used at the same time to heat the metal bath. The influence of this secondary coil is most important, and can best be shown by the fact that with the 1½-ton, three phase, 50 cycle furnace operating at Völklingen, the power factor rose from 0.5% at the start to .8% and above, as the work of the pole plates increased. The secondary winding meanwhile takes up from 20% to a maximum of 30% of the total work of the furnace.

By using the above expedients, which consist of, 1st–the bath resistance being increased within practicable possible limits, 2nd—the coils being wound on two or three cores, and 3rd—the secondary copper coils used to reduce the leakage field, it is possible to build Röchling-Rodenhauser furnaces for standard frequencies, *viz.*, 25 (50 in Europe) and, in the case of very large units, for 15 cycles without the power factor falling below values found elsewhere. Polyphase furnaces of 3½ tons and 50 cycles are quite practical, whereas large sizes up to a maximum of 15 tons would have to be operated with 25 cycles, with polyphase current.

With the given conditions in the secondary circuit of the Röchling-Rodenhauser furnace, the conductor of the second class, which is placed in front of the poleplates must be made to conduct as soon as possible. This is accomplished primarily by giving the conductor as large a cross-section as possible, and making the current path as short as possible, so that the operation proceeds only with very low current densities. In order, however, to force a current passage, and thereby provide as quick a heating up as possible, with the comparatively high resistance of the conductor of the second class, a higher voltage is used

in the secondary circuit during the heating up period, than later, during the regular operation. A convenient expedient for accomplishing this is to alter the number of turns of the secondary winding; this may be accomplished by the use of a single throw-over switch. In this way, for instance, the 8-ton furnace at Völklingen is operated with 20 volts in the secondary circuit, during the heating up period, with the primary voltage remaining the same, whereas, subsequently, *i.e.*, during the normal operation only, 10 volts is used. With this voltage it is possible to conduct several thousand amperes through the current-carrying lining into the molten metal. This naturally brings with it an increased heating effect, even though the main heating is accomplished with the currents directly induced in the bath; also, during normal operation the current encounters a resistance in its path, in the current-carrying mass leading to the bath, similar to the resistance mentioned with carbon electrodes in arc furnaces. In accordance with this, considerable portion of the energy generated in the secondary coil must necessarily be converted into heat in the current-carrying lining. This would, of course, mean substantial losses, provided this heat could not be utilized in the bath. This heat is however utilized as the metal bath is in contact with the current-carrying lining, which may be regarded merely as a heat resistor, the object being of transferring the heat generated in it to the bath. Slight radiation losses only occur as a small percentage in the arms of the poleplates, (which however possess no cooling arrangements), but there are no appreciable losses otherwise, excepting those which for instance are occasioned by the radiation and heat conduction of the insulated heating channels, as already described.

Considering the foregoing, we may regard the Röchling-Rodenhauser furnace as a combination of a pure induction furnace with a pure resistance furnace, so that the usual designation of the furnace as a "combination" furnace is well founded.

If the combination furnace be now compared with the ideal furnace, it may be said concerning the *utilization of every available form of alternating current*, that the furnaces fulfil this requirement to a considerable extent, for they may be built for any

prevailing voltage for either single or polyphase. A certain restriction, however, appears, in that the falling power factor with increasing size furnaces cannot be avoided, even though it is considerably less than with the Kjellin furnace. Single phase furnaces of 3- to 5-ton capacities are practical only for 25 cycles and less; with greater capacities they can only be built for 15 cycles. With polyphase furnaces the drop is not so sensitive, so that here 3-ton furnaces may be built for 50 cycles, and 15-ton furnaces may still be built for 25 cycles.

From what has gone before, it is evident that *sudden power fluctuations* with Röchling-Rodenhauser furnaces are absolutely absent. Where value is placed on machinery having small repairs and long life, these furnaces accordingly mean an ideal load for the central power plant. This is also the case when it is necessary to change the energy supplied to the furnace, and thus raise the temperature to the degree necessary for favorable operation of the metallurgical process. If the furnace is to operate in conjunction with its own generator, it can best be regulated as shown by the wiring of Fig. 80 which is perfectly applicable to the single phase Röchling-Rodenhauser furnace. This method was originally applied at the Röchling works, to an 8-ton Kjellin furnace, and is used unchanged today for a furnace of the same size. In using this scheme it is assumed that the generator is to be used only for the furnace. As it has been shown that the combination furnaces have the advantage that they may be connected directly to existing polyphase circuits of any voltage and frequency, even for furnaces of considerable size, this arrangement becomes particularly interesting. For instance the arrangement may be used at all works which do not desire to erect their own power plant, but wish to use current from a distant central station. It is, however, significant for

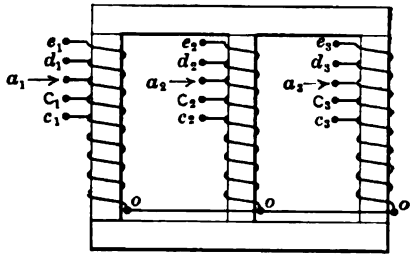



FIG. 98.

works which desire to form a definite and practical opinion of the working operation of the Röchling-Rodenhauser furnaces to do so by means of a small trial installation. Such works would lay the greatest stress on the ability to utilize their existing power plant in order to reduce the initial cost of a trial installation.

In such cases it is necessary to regulate the voltage at the furnace without appreciably disturbing the voltage of the central power plant. This is accomplished by the use of so-called regulating or auto-transformers. Fig. 98 shows the wiring scheme for one of these for three phase currents. If at the points, $a_1$, $a_2$, and $a_3$, for instance, a certain star connected potential of, say, 500 volts is connected, corresponding to a phase voltage of 289 volts, and if there are 289 turns between the neutral point and $a_1$, $a_2$, and $a_3$, then there are only 260 turns lying between the neutral point and the points $b_1$, $b_2$, and $b_3$, there will be only a 260 phase voltage between these points and the neutral point, corresponding to a star connected voltage of $260 \times 1.73 = 450$ volts. In case the primary coils of the furnace are connected with the points $b_1$, $b_2$, and $b_3$, we give them 450 volts in place of the 500 volts of the circuit. Any number of these taps may be brought out of the auto-transformer. For instance, the points $c_1$, $c_2$, and $c_3$, could deliver 400 volts, *provided it is assumed they correspond to about* 230 turns so that a phase voltage of 230 would result. In the same way that a voltage decrease is attained a voltage increase may also be reached. In this way the points $d_1$, $d_2$, and $d_3$ would give 550 volts, and the points $e_1$, $e_2$, and $e_3$, a potential of 600, if the number of turns per core were raised respectively to 318 and 347. It may therefore be seen to be a matter of fact, that the voltages are proportional to the number of turns, and that only one continuous winding per core of the transformer can be used for voltage regulation. A so-called step switch, especially designed, is still necessary, in addition to this transformer, by the aid of which the winding may be switched from one point to another without interrupting the current.

The *electrical efficiency* of a Röchling-Rodenhauser furnace

may be regarded as extraordinarily favorable, for an electric furnace. Measurements taken on a 3½-ton single phase furnace in Völkingen, for instance, gave an efficiency of 96%, notwithstanding that this furnace was the first of the larger ones to be constructed, and could by no means be designated to be especially well dimensioned—as the line losses are extremely low when using high potential directly, and as rotary transformer losses are usually not present, the total electrical efficiency of these furnaces will always be greater than 90%.

It has already been mentioned that the furnaces are of the *tilting variety*.

The requirements of an *easily surveyed and accessible hearth* may be regarded as being fulfilled, as the hearth is central and has two or three operating doors at the sides. There remain, of course, the heating channels at the sides which are not well esteemed by the metallurgist, although they are so arranged that slag cannot enter them, but it must be remembered that they result in a far-reaching circulation on account of electrical conditions, which assures a homogeneous composition of the molten metal both in the channels and in the hearth, so that the heating channels, as a matter of fact, exercise no deleterious influence on the operations.

The *circulation phenomena* in Röchling-Rodenhauser furnaces result advantageously owing to electric and magnetic conditions. Referring to Fig. 99, which shows a hearth of a single phase or two phase furnace, the arrows show the direction of the circulation, which direction may easily be observed in actual practise by throwing some lime dust on the uncovered metal bath. We have also the circulation of the bath against the lining, between the bath and the coil. In addition to this it may be observed that the molten metal is somewhat elevated at the doors, which results in a flow of the fluid mass toward the middle of the hearth on the one hand, and toward the channels on the other. Both manifestations may be defined as being the mildest forms of the pinch effect. This appears as shown in Chapter III, because the fluid conductor flows toward the point of higher temperature. The high current densities are to be found, first, in the middle of

the hearth, and second, in the heating channels, whereas the current densities are decidedly the lowest at the broad sides of the hearth near the doors. There is consequently a suction action, first on the part of the channels, and again on the part of the centre of the hearth. This circulation, based on the pinch effect, has the advantage that it works vertically against the inner lining, and therefore lessens this motion, so that throughout the whole furnace there can be observed only a slow flow, without being violent in any way. A part of the ascending motion of the

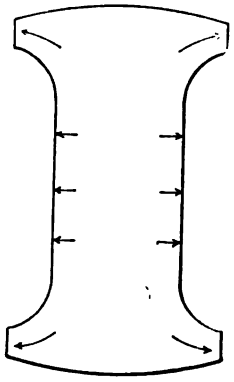


FIG. 99.

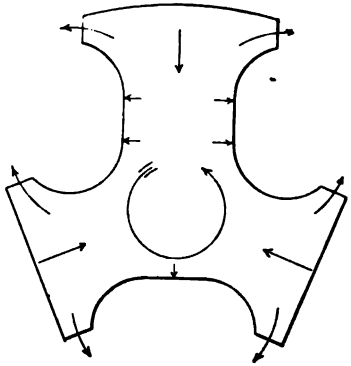


FIG. 100.

fluid metal at the doors is to be accounted for by stronger heating of the bath, occasioned by the heat generated by the current through the current-carrying lining, which naturally results in a rise in temperature of the higher heated material.

Exactly the same reasons cause the circulation phenomena in the three phase furnaces, so that there remains little to be said about it. Fig. 100 shows the circulation phenomena which may be observed in one of these furnaces. This is somewhat different from the single phase furnace, as there is an additional circular motion of the bath between the three cores. This rotary motion is the result of a rotating field, which arises between the three transformer cores and has a similar action to the connected

stator of the polyphase motor, by means of which the armature is caused to revolve. This comparison must not lead one to the erroneous conclusion, that the bath rotates at the same speed as the rotor of a motor would under similar conditions. The motion is also very mild here, and can often only be observed by

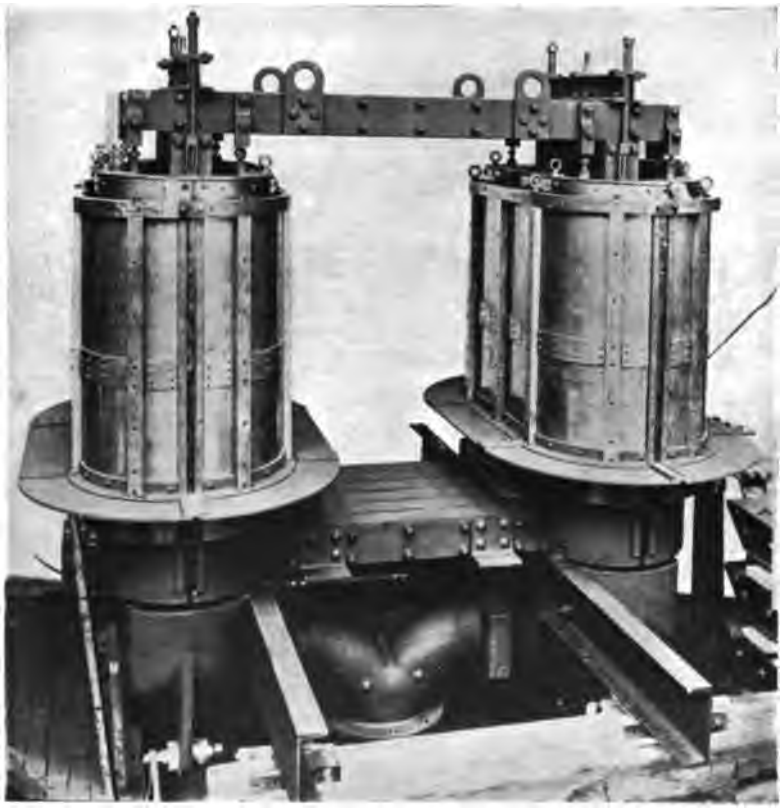


FIG. 101.—Transformer of a single phase furnace.

throwing fine lime on the bare metal. A circulation, such as this, possesses distinct advantages for the metallurgical process. It causes new masses of metal to be brought into contact with the refining slag, also a thorough homogeneity of the contents of the furnace, and finally facilitates the separation of suspended

particles of slag, without having any consequential disadvantages. If, now, the opinion is expressed that the lining does not stand up well under the action of the circulation, this may be accounted for by the fact that the durability of the lining of induction furnaces was short, as compared with that of arc furnaces; but the lining costs per ton of steel were not higher than those of arc furnaces. As a matter of fact the influence of the circulation of the molten metal on the lining is almost insignificant, for the wear takes place only at the slag line and is therefore only to be accounted for by the chemical action of the slag, which can be easily proved by the worn lining at the slag line. Finally, it may be mentioned that the Röchling Iron & Steel Works have been successful in constructing the refractory lining of Röchling-Rodenhauser furnaces to withstand the action of the slag, to such an extent that the durability of the hearth compares very favorably with that of the Girod or Stassano furnaces.

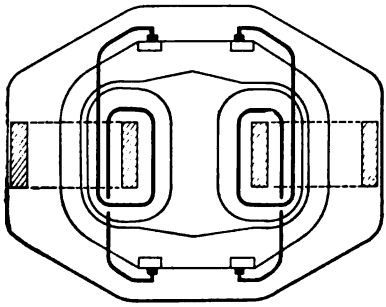


FIG. 101a.—Heavy lines denote the secondary circuit of a two phase R.-R. furnace with two separate pole plates at either end.

Regarding the circulating phenomena, there is still to be mentioned that with very large furnaces, for instance, having comparatively great depths of bath, it may be advisable to obtain a stronger motion in the bath than is possible with the above-mentioned forces. A convenient means for doing this is to increase the pinch effect. In order that this may be accomplished, all that is required is to raise the bottom of the hearth in the centre for a short length. This causes a contraction of the cross-section of the bath at this place, giving a higher density, and consequently a stronger suction action at the centre of the bath which can be increased until the bath becomes wavy, in case the raised portion is made high enough. By means of this

arrangement, therefore, we have a convenient means of increasing the circulating motion to any desired degree.

The Röchling-Rodenhauser furnace is far-reaching in its *application*. The furnaces are adapted to produce any quality of steel from any common raw material. The assurance for this

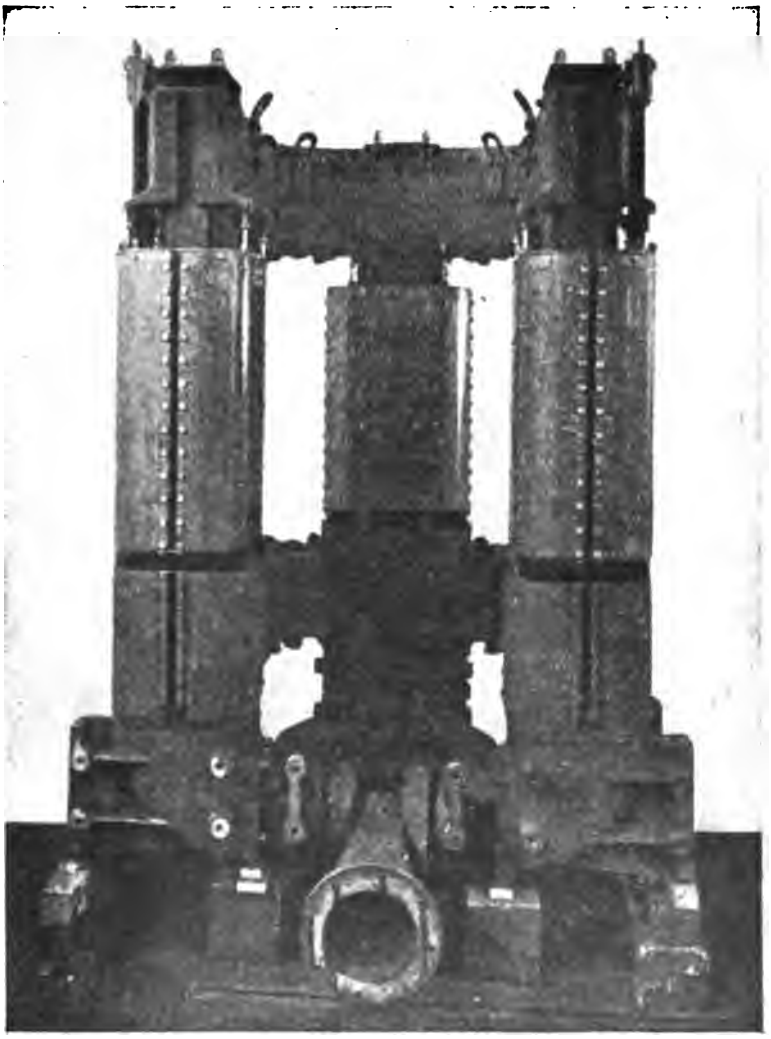


FIG. 102.—Transformer of a three phase furnace.

is given by the similarity of the working hearth to that of the Siemens-Martin open-hearth furnace. It does not seem inappropriate to dwell explicitly on this point at this place, as these furnaces, being a type of induction furnace, were credited with the same weaknesses that the early induction furnaces possessed. These disadvantages appeared with the Kjellin furnace (the first induction furnace which found its way into practical steel making) on account of its peculiarly shaped hearth. This prejudice against the furnaces is, however, entirely unjust. Regarding this, reference is made to the second part of this book, where the best refining results attained with other electric furnaces, as well as with Röchling-Rodenhauser furnaces, are discussed in detail. Of course these furnaces reach a limit of their applicability, when cold stock is to be melted in the same furnace for high class steel alloys with quick changes following each other. In this case, when working up cold stock, the metal remaining in the hearth would interfere with the composition of the next charge. Therefore, if induction furnaces were to be used in this case, two furnaces would be necessary, one of which would be designated to melt the cold metal, and be operated to make a portion of each charge start the succeeding charge, while the second furnace, in which the refining and alloys would be made, could always be charged with hot metal from the first furnace, and would consequently be fully emptied after each charge. With this method of operation it is evident that the previous charge cannot in any way affect the quality of the succeeding one. It requires, however, a comparatively large initial capital, which would only be justified when it would be desired to make large quantities of electric steel. These conditions would make it difficult, if not impossible, for small steel plants to compete with the induction furnace in its present form, when using the above method. On the other hand, in very many other cases, the necessity of leaving some of the metal in the furnace can hardly be regarded as a detriment when working up scrap. This applies particularly to those making electric steel, in the manner it is made to-day, for instance, in large lots to take the place of Swedish iron. For, in this case,

the metal remaining offers the advantage of allowing the melting operation to proceed by using a considerable proportion of the available electric energy left in the remaining metal, even while charging. This results in shortening the melting time, and produces a better efficiency and also a greater production.

A further limitation of the use of electric furnaces may be ascertained by studying the limit of practicability of the furnaces according to their size. It may be mentioned here, that single phase and two phase furnaces are built for a minimum capacity of 300 kg. (660 lb.), and give practical and economically useful operating conditions. If the bath surface becomes too large in proportion to the capacity, then the thermal losses become of such an extent that an economical operation would no longer be possible. The useful limits of these furnaces for the iron industry lie therefore within the sizes mentioned above and below.

The largest Röchling-Rodenhauser furnace unit so far built has a capacity of 8 to 10 tons. This gives excellent operating results at the works of the Röchling Iron & Steel Works. This size furnace, though, in no way indicates the upper limit of its practicability or of the economical usefulness of the furnace. Complete constructional details have been worked out for furnaces of the 25-ton size, so that this size may be regarded as the upper limit, for the present, with which good operating results may be determined with certainty.

The thermal efficiency of the furnace may best be judged by the total efficiency. That the efficiency of furnaces becomes better with increasing sizes, is true as it is with other furnaces previously discussed. We find that the smaller sizes, adapted to single phase, are considerably superior to the three phase, considering their total efficiency, whereas when the capacity reaches 3 tons the efficiencies are about equal, while for larger sizes than this the polyphase furnace is the better. The reason for this arises from the fact that single phase furnaces, even of the 3-ton size, must be operated from as low as 25-cycles, whereas three phase furnaces of this size may be operated to advantage with 50 cycles. Lowering the frequency necessitates enlarging

the cross-section of the transformer, which means more space for the coils, and hence a larger periphery of the walls touching the bath surface, so that with a 3-ton single phase furnace we have a larger bath surface, with a lesser bath depth, than with a

FIG. 103.

three phase furnace of the same size, which has a smaller bath surface with a greater depth of bath.

Even though the single phase furnace up to the 3-ton size is preferable to the three phase furnace on account of its efficiency, these conditions, however, become a deciding factor only when a new generator is to be furnished for the furnace in either case. If, on the other hand, an extensive power plant producing a certain type of current already exists, then the choice of furnaces would in most cases be decided by the actual current available, in case this could be used directly in a single, two, or three phase furnace. In these cases, when using the existing current directly in the furnace, the deciding factor would be the avoidance of the rotary transformer losses, which are always about 15 to 20%, and therefore so large that, as far as the total efficiency of

a furnace installation is concerned, they would be bound to be the deciding factor.

In discussing the question of efficiency, the following will be of interest: The total (net) efficiency of a 1½-ton three phase furnace at the Röchling Iron & Steel Works was 60%, when comparing the theoretical figures and the actual amount of energy used in melting up cold scrap. The total efficiency of the 8-ton furnace operating at Völklingen was determined by the fact that it took 580 kw. hrs. to melt one ton of common scrap. If we compare this with the required theoretical energy, which was placed at 489 kw. hrs. in the previous chapter, we find that the 8-ton Röchling-Rodenhauser single phase furnace has an efficiency of $\frac{489}{580} = 85\%$.

Even though these figures may not be called absolutely correct, on account of unavoidable irregularities or uncertainties creeping into the theoretical computations of the energy required, still the fact remains that the required power of 580 kw. hrs. was all that was needed to melt one ton of common commercial steel scrap, so that the efficiency figures retain their full accuracy and significance as relative figures of comparison. Considering the heat losses, these results show that, in spite of the really unfavorable arrangement of the hearth with the side connecting channels, efficiencies are still attained, which are fully equal to those of the Kjellin furnace, with its ring formed hearth, and they may also be considered as comparing most favorably with the efficiency of any arc furnace.

In adding a few words here on the *installation cost*, reference is made to a 5-ton polyphase furnace which is to be connected to an existing power plant. This would operate in conjunction with a separate transformer and a multi-point switch and would cost about $18,000. This price includes the furnace, the furnace transformer, the switchboard, the electrical tilting mechanism, etc. It, however, does not include the generator installation, which was assumed to be already in existence.

The following references are to the figures which augment the text. Fig. 101 shows the transformer of a single phase

Röchling-Rodenhauser furnace, while Fig. 102 shows the transformer for a three phase furnace. From the figures one can plainly perceive the arrangement of the cores and yokes. The former are covered by the protecting cylinders, as these figures show the manner in which the ventilating air is conveyed by means of a central air duct, as shown in Fig. 88. The bifurcated air-supply duct which lies between this central duct and the cores

FIG. 104.

is also plainly distinguishable in Fig. 101. Such furnace transformers are then built directly into the furnace brickwork or into the furnace refractories, which thus decide the appearance of the furnace. Fig. 103 shows an 8-ton single phase furnace in its tilted position, and Fig. 104 a three phase furnace of 1½ tons capacity.

The sale of these furnaces and the giving of licenses are conducted in Continental Europe by the *Gesellschaft für Elektrostahlanlagen, Berlin, Nonnendamm;* for England and her Colonies except Canada by the *Gröndal Kjellin Co., London.* In the United States and Canada formerly by the *American Electric Furnace Co., New York,* at present by *Siemens and Halske, A—G—, New York.*

# CHAPTER XIII

## THE ELECTRIC SHAFT FURNACE

In the consideration of electric furnaces that one must not be overlooked which may be briefly called the Electric Shaft Furnace. It is to serve to replace the ordinary blast furnace.

From early times efforts have been made in countries rich in ore and water-power, but poor in fuel, to replace the fuel used in the blast furnace for the production of heat, by electricity, and so lower the fuel consumption. In the electrical process of pig-iron production there only remains about one-third of the fuel consumption necessary in the ordinary blast furnace, and this is for reduction only. In this way about two-thirds of the fuel cost is saved. At the same time the large blowing engines of the ordinary blast furnace are not required. These are the two important things that promise success to a good solution of the question of the electrical smelting of iron ore.

Even in the introductory period of practically useful electric furnaces we find that they were first adapted to the production of pig iron. The Stassano furnace is an example which was originally only constructed for the smelting of ore. It is shown in Fig. 44, which clearly brings out how similar it is in construction to the ordinary blast furnace. Stassano's experiment was unsuccessful, and we have seen how he turned to the method worked out in the meantime at La Praz by Héroult, for the utilization of scrap. Tests were also made in those parts of France having abundant water-power. Here Keller and Héroult were occupied with the question, and many reports and discussions of their experiments appeared in the journals in the middle of the last decade.

The furnace used by *Keller* is shown in outline in Fig. 105. Two shafts are joined at the bottom by means of a channel. At the base of each shaft is a carbon electrode, these electrodes

being connected by means of an outside cable. A carbon electrode is hung in each shaft. At the beginning of the operation the current flows from one carbon electrode and through the charge in the corresponding shaft to the bottom electrode. From here it goes through the outside cable to the bottom electrode of the other shaft, through the charge, and to the second electrode. As the smelting proceeds the connecting channel becomes filled with molten iron. As soon as a connection is made in this way between the two shafts the current flows through the molten material, which offers a much lower resistance than the two bottom electrodes and the outside cable. In the middle of the channel is the tapping hole.

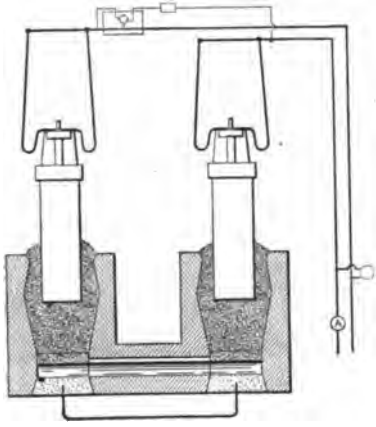


FIG. 105.

In a later construction Keller had a third small carbon electrode, which was lowered into the connecting channel, and was used to keep the metal there thoroughly liquid. Extensive tests were made with this later furnace at Livet in 1904, at the time of the visit of the Canadian Commission under *Dr. Haanel.*

Of lesser importance were the tests carried out by Héroult, at La Praz, in the presence of the Commission. German Patent 142,830, 1902, shows that Héroult had not left the subject of the smelting of ore in the electric furnace without attention, although he worked, at first, to develop a process for using scrap-iron and steel. This patent was granted on an electric furnace with electrodes built in the hearth and the shaft. It is shown in Figs. 106 and 107. It was not successful, and Héroult in his tests before the Commission mostly used a simple type similar to one-half of the Keller furnace. His average production with such a furnace at that time was 7.82 metric tons per 1000 E.H.P. days.

In the time immediately following the visit of the Canadian Commission no further experiments in the line of pig-iron production were made in Europe that are worthy of notice. The general attention was devoted to the production of electric steel and iron for the very good reason that the results so far obtained

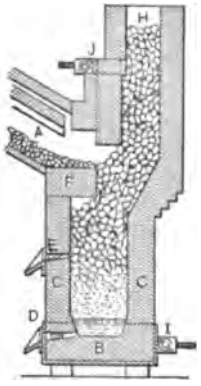



FIG. 106.

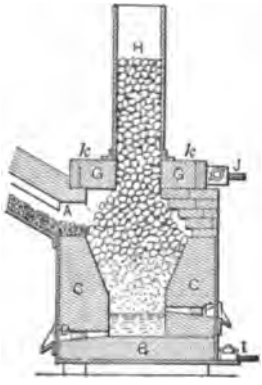



FIG. 107.

in the production of pig iron showed no promise of success in Europe, for a great number of years, in competition with the highly developed ordinary blast-furnace process.

On the other hand tests were continued in Canada, to which country Héroult went in December, 1905, his experiments being made in January, 1906. They were mostly carried out with the furnace shown in Fig. 108, consisting of a crucible with a shaft above it. The bottom, being made of electrode carbon, forms one pole, the other being a hanging carbon electrode. This electrode had a length of about 5′ 10.8″, and a cross-section of about 16″ x 16″. The maximum current was about 5000 amperes, with a pressure of 35 to 40 volts and a power factor of $\cos \phi = 0.9$. The results under normal conditions were the production of about 11.5 metric tons of pig iron per 1000 E.H.P. days. Although good results were obtained with various ores, judging from a metallurgical standpoint, it was seen that an electrode entering the furnace with the charge would not satisfactorily solve the problem. For instance the electrode frequent-

ly rose higher and higher in the shaft of the furnace, so that the material in the bottom got colder and colder. This was caused by the charge becoming too dense, and not allowing the gases to escape easily enough. In this way the resistance between the two poles was lessened, and the voltage remaining the same, the upper electrode rose in the furnace. It also brought about considerably higher electrode consumption. To sum up the question, a successful electric shaft furnace was not solved by the experiments made in Canada.

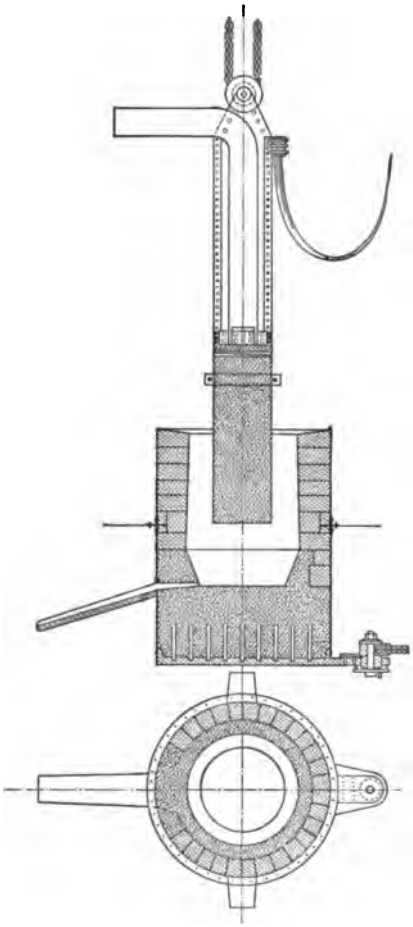


FIG. 108.

In the spring of 1907, experiments with electric pig-iron production were begun in Sweden. Messrrs. Grönwall, Lindblad and Stalhane together formed the "Electrometal" Company, with the aim of building and selling electric furnaces. The tests which will now be considered in detail were carried out by them at Domnarfvet. According to Yngström's careful report in the *Jern-Kontorets Annaler*, No. 9, 1909, a current of 7000 volts at 60 periods was used. With this current a 900 HP motor was driven, directly coupled to a 25 period, three phase generator. From this generator the current was led directly

to the transformers which were arranged near the furnaces and served them. Here also a switchboard with the necessary measuring instruments was set up. These included a watt-meter, three ammeters, and one voltmeter. Underneath were the hand wheels for regulating the electrodes.

*Grönwall*, *Lindblad* and *Stalhane* first made use of the results of the former experiments. They therefore endeavored to completely obviate the use of hanging electrodes, and to keep the current in the hearth of the furnace. Fig. 109 shows the first test furnace, which was built to take single phase current. Each pole consists of a copper plate carrying a graphite block. These blocks are hollowed and lie outside of the furnace proper. Channels lead from them into the furnace which, when filled with molten iron, serve to conduct the current to and through the charge. Besides these two conduction channels that are arranged on one side of the furnace, there is a third one, as may be seen in the illustration, and which serves for tapping the furnace.

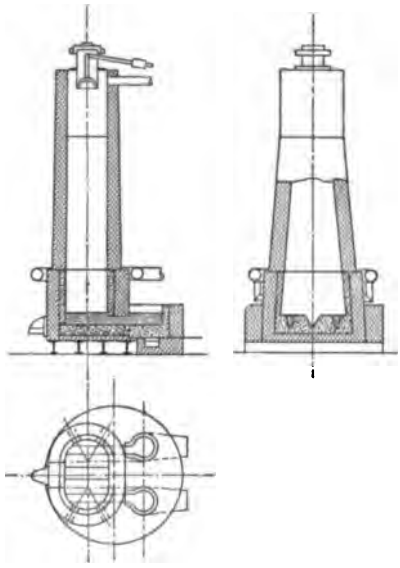


FIG. 109.

After charging, the furnace is run precisely as an ordinary blast furnace, until a considerable amount of metal has collected in the hearth. This insures good conduction from the carbon electrodes to the interior. The blast is then stopped, the current switched on, and the electric heating begun.

The course of the current was arranged as follows: It entered at one pole and passed through the metal lying over it into the metal in the channel at one side of the furnace proper,

from here through the charge to the metal in the channel at the other side, and so to the outgoing pole. Heating is brought about through an overheating of the liquid contents of the furnace on the one hand, and the resistance offered by the charge on the other. This should furnish heat sufficient to smelt the ore. The hearth was made of quartz. In operation it only lasted a very short time, so that the furnace could not be operated for very long. This was because its wave-like surface offered conditions favorable to attack, and brought about quick destruction at the high temperatures reached.

The first necessity was to rebuild the furnace. This was done in such a way that the electrodes led into the furnace from opposite sides, as is shown in Fig. 110. At the same time it was hoped that the use of magnesite in the hearth would give better service. This, however, was not the case, for the reason that the magnesite, a fairly good conductor even at ordinary temperatures, became too good a conductor at a high temperature, and the experiment had to be stopped. This second test showed the impossibility of satisfactorily leading the strong current necessary for heating a shaft furnace into the charge from the bottom. This style of furnace was therefore rejected.

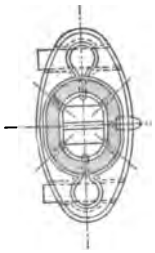


FIG. 110.

The third test furnace approximates in form the one already proposed by Héroult in his patent of 1902. It is shown in Fig. 111. The shaft-like construction is furnished with three electrodes, of which one forms the bottom, while the two others are arranged on opposite sides at a medium height. The direction of the current can be so arranged that it either flows horizontally from one shaft electrode to the other, or else goes out through the bottom electrode. In operation the shaft electrodes were destroyed so rapidly that they were replaced by ordinary water cooled electrodes with continuous feed. With this arrangement considerably better results were obtained, but the walls near the shaft electrodes were so rapidly destroyed, because of the intense heat generated, that this style of furnace was also rejected

as unsatisfactory. It, however, pointed the way to a good solution of the question. If care was taken to keep the intense heat, which is produced where the electrodes and charge come in contact, away from the walls, then more favorable results and a greater furnace life would be obtained. These considerations led to surrounding the electrodes directly with the charge, so that the heat, which was formerly lost through the walls, could now be used for heating the charge, and at the same time a much greater durability of the furnace walls was obtained.

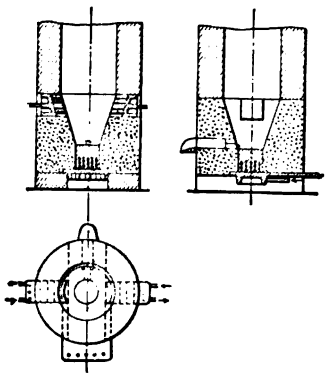


FIG. 111.

The 1909 test furnace is shown in Fig. 112, the lower part of which may be considered as the final form of the electric shaft furnace. This is the furnace of Grönwall, Lindblad and Stalhane. It has three electrodes penetrating the roof of this hearth and is in general very similar to the ordinary blast furnace, except that the tuyères are replaced by electrodes. The results show that this construction in its 1911 and 1912 improved form is the most complete and suitable produced, and is the only one worthy of serious consideration. A detailed description is given below.

The smelting part of the 1909 furnace forms a large crucible or hearth 7′ 4½″ in diameter, 4′ 11″ high. It is lined with magnesite. The shaft of the furnace is arranged above the hearth, and has a height of 17′ with an interior diameter of 4′ 3″ at the widest part. The shaft is supported by a steel framework resting on six iron columns. This makes it possible to independently repair the hearth. The charge falls from the shaft into the hearth through an opening arranged in the roof. It forms an angle or slope of about 50° to 55°. This produces a free space between the charge and the roof and walls of the hearth, on which the greatest importance is to be placed. It serves to cool the electrodes and the walls of the furnace. To help in this

purpose the cool waste gases from the top of the shaft are taken and blown through tuyères into this cooling space. This method also brings heat back to the furnace, and so gives a better heat efficiency. As Fig. 112 shows, three carbon electrodes penetrate the roof of the hearth. In the 1910 model four electrodes, and in the 1911–1912 model six electrodes, are used. The early electrode

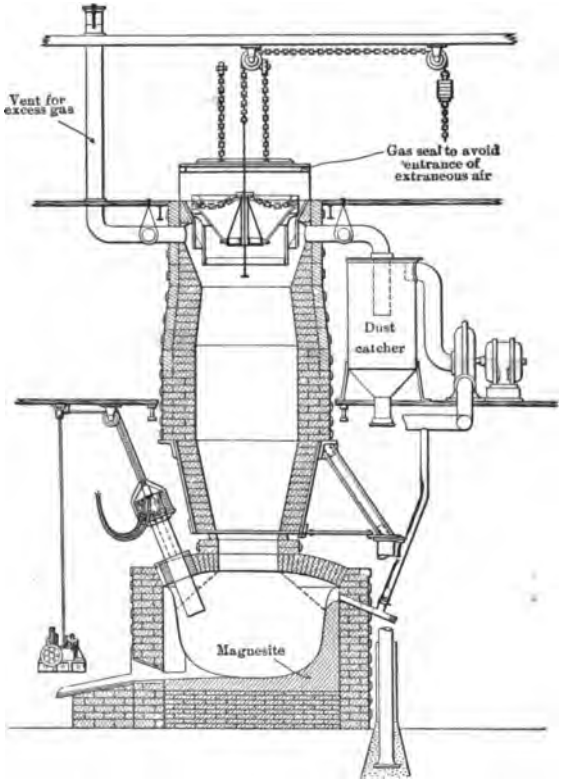



FIG. 112.

consisted of two carbon blocks 13″ square, so that the total cross-section is 169 sq. ins. The electrodes are made in Sweden from retort carbon, and permit the use of a current of 25.8 amperes per sq. in.

The electrode holders consist of strong steel frames. These

are provided with several wedges by means of which the copper plates that carry the current from the cables to the electrodes are firmly pressed against the latter. The electrodes are operated by hand, and the part projecting from the furnace is provided with an asbestos cover to prevent oxidation. The openings for the electrodes have water-cooled seats, and arrangements are provided to prevent the escape of gas.

When the furnace is put in operation it is run, at first, exactly like an ordinary blast furnace. The electrical heating is only used later. The furnace now described was run, with slight interruptions, from May 7, 1909, to the end of July. The following notes, taken from the account of the operations, are of special interest. At the beginning of the electric heating the current goes chiefly through the upper part of the charge, which means that the largest amount of heat is produced immediately under the roof, which is strongly heated and partly destroyed. One reason for this is that the lower part of the charge is colder, and therefore offers greater resistance than the upper part. The conditions were greatly improved as soon as the waste gases were blown in. The temperature of the roof was lowered, and the hottest zone sank lower and lower. The result was a lowering in the resistance of this part of the charge, so that the current found a more favorable path, and was concentrated in the lower part of the hearth. When this condition was once reached a five days' interruption of the gas-cooling brought about no change from normal running.

During the operation of the furnace no big fluctuations of the current were noticed, and even during tapping the instruments remained steady. This leads to the conclusion that the resistance of the charge was very constant. The electrodes required very little attention. They were regulated once a day on the average, and in one case they were not touched for five days.

The maximum current amounted to 9000 amperes per phase. With 25 cycles a power factor of 0.8 to 0.9 was obtained, with 60 cycles of about 0.7, and other calculations gave 0.535. Naturally with a fixed cross-section of electrodes the amount of energy

that can be used is dependent upon the permitted potential, which in its turn depends upon the resistance of the charge. The higher this resistance, the higher can the voltage be without the strength of current overstepping the permitted maximum. It is therefore of interest to know how to influence the internal resistance, and this consists in the choice of the proper amounts of ore and fuel in the charge. In the following table are given the strengths of current reached with various burdens, and with fixed voltages.

| Charge with | Potential between two Two Phases in Volts | Current Strength per Phase Amperes | Power with an Average Cos $\phi = 0.85$ $A = 1.73\ ei \cos \phi$ |
|---|---|---|---|
| Coke in excess | 34 | 9,600 | 480 kw. |
| Coke not in excess | 36 | 8,800 | 465 " |
| Too little charcoal | 60 | 6,300 | 555 " |
| Sufficient charcoal | 54 | 7,600 | 603 " |
| Too much charcoal | 48 | 7,600 | 536 " |
| Too much coke and charcoal | 35 | 9,200 | 471 " |
| Sufficient coke and charcoal | 48 | 7,600 | 536 " |

The operation of the furnace was very simple and uniform, the metal being tapped about every six hours. When judging the efficiency of the furnace it should be remembered that the following sources of loss are to be considered:

1. Cooling of the electrodes with water.
2. The ohmic resistance of the conductors and contacts.
3. The radiation from the furnace.

The total loss amounted to from 230 to 270 kw., the higher value coming at the end of the run. The loss is divided about as follows: The water cooling carries away from 118 to 225 kw., which, with a power of about 500 kw., corresponds to a loss of about 25 to 30%. Overcoming the contact resistance takes about 40 kw., and from 110 to 180 kw. are lost by radiation. The electrodes lose 5.8 kg. (12.8 lb.) per metric ton by burning away, the total consumption being 13.8 kg. (30.4 lb.) per metric ton. From another source (E. F. Ljung-

berg, *Metallurgie*, November, 1909), the consumption of electrodes through burning is 8.8 kg. (19.4 lb.), and through waste ends 13.9 kg. (30.6 lb.), a total of 22.7 kg. (50 lb.) per metric ton. This large difference between the loss by burning and the total consumption is brought about by the electrodes not being completely burnt, and the ends having to be replaced by new ones. There is no loss from stub ends in the later designed electrodes which are screwed together.

The maintenance cost of the furnace could not be determined exactly, but the furnace worked satisfactorily for 85 days without a stop. The weakest place is the roof of the hearth, which is exposed to the intense heat generated at the electrodes. According to Ljungberg, 891,623 kw. hours were used to produce 280 metric tons. This means 0.492 h.p. years or 3184 kw. hours per metric ton of pig iron. This is a high figure and has since been lowered to less than 2000 kw. hours, or 0.31 h.p. years, on long runs.*

The following tables give the efficiency obtained during the test with different burdens:

| Charge No. | Carbon Consumption (pure carbon) | | Amount of Theoretical Energy Necessary with the Given Carbon Consumption kw. hrs. | Real Power Consumption | | Electrical Efficiency |
|---|---|---|---|---|---|---|
| | Kg. | Lb. | | kw. hrs | H.P.Year 365 days | |
| 3 | 252 | 555.5 | 1,470 | 3,114 | 0.483 | 47% |
| 4 | 254 | 560.0 | 1,438 | 2,473 | 0.383 | 58 |
| 5 | 284 | 626.1 | 1,741 | 3,245 | 0.505 | 54 |
| 6 | 294 | 648.1 | 1,870 | 3,334 | 0.517 | 56 |

The economy of making pig iron in the *Grönwall, Lindblad & Stalhane* furnace is given in the chapter on operating costs, hence the following table by *Catani* is of interest. It is quoted from Neumann, *Stahl und Eisen*, 1909, p. 276. This table shows how high the price of current per h.p. year can go, with coke at a fixed price, for the electric shaft furnace to compete favorably with the ordinary blast furnace:

* See page 238.

| Pig Iron Produced per 24 hrs. per H. P. | | Coke Price | | | |
|---|---|---|---|---|---|
| Kg. | Lbs. | $3.81 | $5.71 | $7.61 | |
| 6 | 13.2 | 4.88 | 7.30 | 9.76 | Price of |
| 8 | 17.6 | 6.09 | 9.14 | 12.19 | Power |
| 10 | 22.0 | 7.61 | 11.42 | 15.23 | per |
| 12 | 26.4 | 8.57 | 12.85 | 17.14 | h.p. year |

For comparison with the foregoing figures of the first tests in 1909, the 1910–1911 tests results are here recorded.

The November, 1910–April, 1911, test furnace of 2500 h.p., of Grönwall, Lindblad & Stalhane, is shown in vertical cross-section by Fig. 124. During the run the furnace was operated with four electrodes penetrating the roof, the furnace being operated with two phase current, from a three phase circuit by means of Scott connected transformers. The incoming current is 10,000 volts, three phase, 25 cycles. The secondary volts can be regulated between 50 and 90 volts from the high tension side. The arrangements are such that the different phases can work simultaneously with different voltages. The method has greatly facilitated the working. Regulation is also had by different switching from the low tension side. The newer 3500 h.p. furnaces for Hardanger, Norway, using coke instead of charcoal, have the following dimensions:

| | | | |
|---|---|---|---|
| Diameter of hearth | 3 | meters = | 10 ft. |
| " at ring | 1.5 | " = | 5 " |
| " at boshes | 2.15 | " = | 7 " |
| Height of shaft | 12.0 | " = | 40 " |
| Total height of furnace | 13.7 | " = | 45 " |

These Norway furnaces are somewhat different from the Trollhättan furnace. The volume of the shaft is smaller, but its diameter is greater than the corresponding shaft of a charcoal furnace. The coke in the charge gives it greater conductivity, so that a lower voltage is used.

The ratio of volume of charge per day to shaft volume has been taken at 1.55, and the furnace volume has hence been

made 38 cubic metres (about 500 cu. ft.). The furnace hearth is lined with magnesite. The general contour of the furnace walls and roof over the hearth can best be seen by consulting Fig. 124. The roof is cooled as described under operating costs. The gas that is blown through the tuyères is cleaned in a water scrubber in the latest designs, as shown in Figs. 126 and 127. The electrodes used during the beginning of 1911 were built up of 4 carbons—2 metres (6½ ft.) long and 330 x 330 mm. (13″ x 13″) section arranged to form an electrode 660 x 660 mm. (675 sq. in.) section. 17,000 amps. is the permissible maximum or 25 amps. per sq. in. Toward the end of the year this has been changed to a cylindrical electrode of 600 mm. (23.6 in.) diameter, which is gripped much shorter than formerly (see Fig. 125), thus saving 40 kw. The square electrodes were supplied by both the Plania Works of Ratibor, Germany, and from the Höganäs Works, Sweden. The 600 mm. round electrodes have lately been furnished by the former works and by Siemens Bros. & Co., Litchenberg, near Berlin. The upper part of the electrodes is covered with sheet asbestos and thin sheet-iron, and the top surface is covered with a thick layer of ground asbestos and silicate of potash. They also have a water-jacket, beneath which gas was blown to cool the roof (see Fig. 124). This practise was not long continued, as the $CO_2$ burned holes in the electrodes.

When starting the furnace, it is thoroughly dried out with wood and charcoal fires, and heated up electrically by filling the hearth with coke and turning on the current. About 3 weeks is taken to burn through an electrode above the so-called "stock line." During January, 1911, the average voltage on each phase was 62.6 volts, and the average current per phase 14,449 amps. The average reading on the wattmeter was 1535 kw.; the power factor was consequently .88 + %. The efficiency of the furnace has been greatly increased since the tests were made with the 800 h.p. furnace at *Domnarfvet*, and is discussed under operating costs.

The following table indicates the efficiency obtained during the tests as indicated:

| Date | Percentage Iron in | | Slag per Ton of Iron | Charcoal per Ton Iron Containing | | | | | Total | | Electric Power | | | | | | Electrode Consumption per Ton Iron | | $CO_2$ by Volume |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | Time Used | | | | kw. hrs. | Tons Iron | | | |
| | Ore | Charge | | Water | Gases | Ash | C in | % C | kg. | lb. | For Working. Hours | For Interruptns. Hours | Total Hours | Average Load kw. | Used per Ton Iron | per kw. Year | Gross | Net | |
| | | | kg. | kg. | kg. | kg. | kg. | | | | | | | | | | | | |
| 1910 Nov. 16 to 1911 Feb. 11 | 65.57 | 62.10 | 205 | 69.1 | 41.7 | 11.8 | 293.1 | 70.5 | 415.7 | 916 | 2,009 | 105 | 2,115 | 1,319 | 2,296 | 3.82 | 11.24 | 5.83 | Jan. 3 28.2% |
| 1911 Feb. 11 to Feb. 19 | 65.06 | 62.56 | 224 | 50.8 | 36.9 | 11.0 | 277.6 | 73.7 | 376.3 | 830 | 184 | 4 | 189 | 1,694 | 2,149 | 4.08 | 10.84 | 5.24 | Jan. 14 27.2% |
| Feb. 19 to Mar. 19 | 49.50 | 42.42 | 780 | 59.8 | 49.3 | 13.2 | 323.4 | 72.5 | 445.7 | 983 | 639 | 20 | 660 | 1,017 | 2,623 | 3.34 | 9.19 | 4.52 | Mar. 16 12.6% |
| Mar. 19 to Apr. 9 | 57.92 | 53.06 | 458 | 40.2 | 43.1 | 17.2 | 325.7 | 76.4 | 426.2 | 930 | 506 | 22 | 528 | 1,733 | 2,643 | 3.31 | 7.45 | 3.87 | Mar. 16 19.2% |
| Aver. or Total Above | 61.54 | 57.00 | 327 | 60.9 | 42.9 | 12.8 | 301.4 | 72. | 418.0 | 922 | 3,348 | 153 | 3,501 | 1,344 | 2,391 | 3.66 | 10.28 | 5.27 | ..... |
| 1911 Sept 3 to Sept. 9 | ..... | ..... | 168 | ..... | ..... | ..... | ..... | ..... | 336. | 741 | 168 | 0 | 168 | 1,357 | 1,736 | 5.05 | Less than 10.28 | Less than 5.27 | 30 % |
| Sept. 3 to Sept. 30 1911 | 67.65 | 65.02 | 165 | ..... | ..... | ..... | ..... | ..... | 339.9 | 748 | ..... | ..... | 672 | 1,407 | 1,749 | 5.01 [1] | Less than 10.28 | Less than 5.27 | 29.3% |

[1] Average analysis of iron C = 3.64%, Si = 36%, Mn = 40%, S = .009%, P = .018%.

Comparing the last two sets of figures with the first four sets, it will be seen what a great improvement has been made during 1911. Comparing the above with the 1909 tests shown on page 235, the improvement deserves the recognition it has received, in that over 30,000 h.p. of these furnaces have since been built or are building.

It is interesting to know exactly what the first large 2500 h.p. furnace installation of Grönwall, Lindblad & Stalhane cost at Trollhättan, which has a daily capacity of about 20 tons. The furnace house is of steel construction, and brick and both furnace and electric equipment cost more than a subsequent similar installation would, as this was the first one of this size. The cost was as follows:

| | |
|---|---|
| Excavation, railway connection, water-pipes, scale, etc. | $10,727 |
| Buildings: Furnace house | 14,735 |
| Charcoal storage-house | 6,032 |
| Crusher-house, office, laboratory, shops | 3,961 |
| Furnace | 13,111 |
| Electric equipment | 13,782 |
| Cable and wires | 3,832 |
| Gas-motor, pumps, reservoir | 3,222 |
| Crushers | 1,011 |
| Transformers | 3,433 |
| Motors for crushers, etc | 1,724 |
| Laboratory equipment, furniture, etc | 10,430 |
| | $86,000 |

In order to give an idea as to the size of the necessary plant, it may be said that an output of 10.65 kg. (23.45 lbs.), per h.p. day corresponds to a power consumption of 1736 kw. hrs. per metric ton. With a daily output of 300 metric tons this would need about 35,000 h.p. at the furnace, or about 38,500 h.p. at the power station, when allowing for a long transmission line. If a plant is built for $50.00 per h.p., it would require a capital of $1,925,000. Allowing 9% for interest and amortization, and 3% for taxes, etc., each h.p. year would cost about $6.00 at the power station, or about $7.50 at the furnace.

A complete furnace installation for 300 tons would cost about $500,000 and consist of six furnaces of 7,000 h.p. each,

one furnace remaining in reserve. This estimate is based on the installation costs already obtained, but each furnace would be larger.

It only remains to mention that because of the very favorable results obtained at *Domnarfvet*, 1909, the Jernkontoret of Stockholm has acquired the patents of Grönwall, Lindblad & Stalhane. The British owners of these patents are the Electro Metals, London, whose American and Canadian representative is Dr. D. A. Lyon, Pittsburg, Pennsylvania.

The following iron ore reduction or electric pig-iron furnaces are built or building:

| System | No. | User | Output Tons per Day | | | Kind of Current | Amount of Power h.p. | Reducing Material |
|---|---|---|---|---|---|---|---|---|
| | | | In Operation | Not Working | Building | | | |
| Grönwall, Lindblad & Stalhane. or "Electro-Metal" | 1 | Jern-Kontoret Trollhättan, Sweden | about 20 | | | 3 phase, 25 cycles | 2,500 | Charcoal |
| | 2 | Domnarfvet, Sweden | about 30 | | | 3 phase, 25 cycles | 3,500 | Charcoal |
| | 3 | Hardanger Elektriske Jern Og Staalverk, Norway. | about 25 | | | 3 phase, 25 cycles | 3,000 | Coke |
| | 4 | Hardanger Elektriske Jern Og Staalverk, Norway. | | | about 25 | 3 phase, 25 cycles | 3,000 | Coke |
| | 5 | Hagfors, Sweden | about 25 | | | 3 phase, 25 cycles | 3,000 | Charcoal |
| | 6 | Hagfors, Sweden | about 25 | | | 3 phase, 25 cycles | 3,000 | Charcoal |
| | 7 | Aktie Selskab Fossekompagni, Arendal, Norway. | | | about 25 | 3 phase, 25 cycles | 3,000 | Coke |
| | 8 | Aktie Selskab Fossekompagni, Arendal, Norway. | | | about 25 | 3 phase, 25 cycles | 3,000 | Coke |
| | 9 | Aktie Selskab Fossekompagni, Arendal, Norway. | | | about 25 | 3 phase, 25 cycles | 3,000 | Coke |
| | 10 | Switzerland | | | about 20 | | 2,500 | |
| Héroult, Lyon | 1 | Noble Electric Steel Co. Héroult, Shasta Co., California | about 15 | | | 3 phase, 60 cycles | 2,000 | Charcoal |
| Bie Lorentzen | 1 | Nottoden, Norway | | | about 40 | | 5,000 | |

# CHAPTER XIV

## GENERAL REVIEW

In addition to the methods of furnace construction previously described there are naturally a tremendous number of proposals for the design of electric furnaces. This is best brought out by the many patents that have been issued both for arc and induction furnaces. Although the literature of such patent papers may be very entertaining, and is indeed very often instructive, yet a consideration of the many proposals does not lie within the scope of this book.

Most of them are only proposals and will never be tried out. A smaller number disappear quickly after a trial and leave no trace, while the third and smallest part stand trial in one or another plant. They make possible the saving of the license fee for a successful furnace, but most of them cost enormous sums for experiments, and very often complications develop when they are put in operation.

Although they are not for the most part of value to many people they yet have the advantage that they help to spread the knowledge concerning the properties of electric furnaces further and further. On the other hand, it is naturally only through a fresh consideration of the new methods of construction that a further perfecting of the old or even new ways can be found for reaching the wished-for goal.

On this account, therefore, it is perhaps justifiable to consider at least a few of the furnaces differing in construction from those used most frequently today. Another reason is that one or the other of them are sometimes discussed in the technical literature.

Under the heading of arc furnaces comes first that of *Chapelet*, which is in use at the plant at Allevard (Isère). It is shown in Fig. 113. We see that the current flows in an arc to the bath

from a hanging regulated carbon, similarly to the Girod furnace. From the bath it goes through a horizontal channel to a hanging cast-iron electrode that touches the channel. This constitutes the peculiarity of the furnace. It is not apparent that this arrangement offers any advantage over that of the Girod furnace. In the first place the furnace construction is much more difficult and not so accessible as that of the Girod. Further it is to be feared that the metal in the channel between the outer electrode and the bath will force up the furnace bottom, except that part which is not molten, because of the influence of the water cooling used for the iron electrode. This will bring about difficulties in maintaining the lining, since repairs to the horizontal channel are scarcely possible. The method of working is exactly the same as that of the Girod furnace, that is to say, that heat is produced exclusively by the arc, the resistance offered to the current by the molten material not being of any noticeable value.

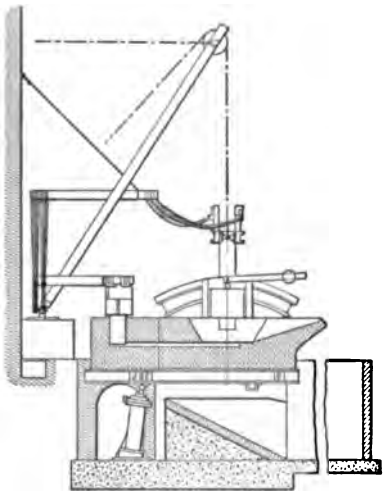


FIG. 113.

The details of construction offer little that is worthy of attention. Water cooling is used at the opening in the furnace roof for the entrance of the carbon electrode, at the outer iron electrode, and also at the carbon electrode connections where the current passes from the copper cables. The cylindrical furnace roof is removable. The openings in the front part of the roof are used as working doors, as shown in the illustration. There are several of these furnaces in Allevard, but, according to Coussergues' report, only one is in operation.

The Keller furnace, shown in Fig. 114, has still greater

similarity to the Girod furnace. The only difference is a special arrangement of the bottom electrodes. While Girod, as we have seen, uses several water-cooled steel electrodes that are distributed over the bottom surface of the hearth, Keller uses a furnace bottom formed of a so-called *mixed conductor*. As

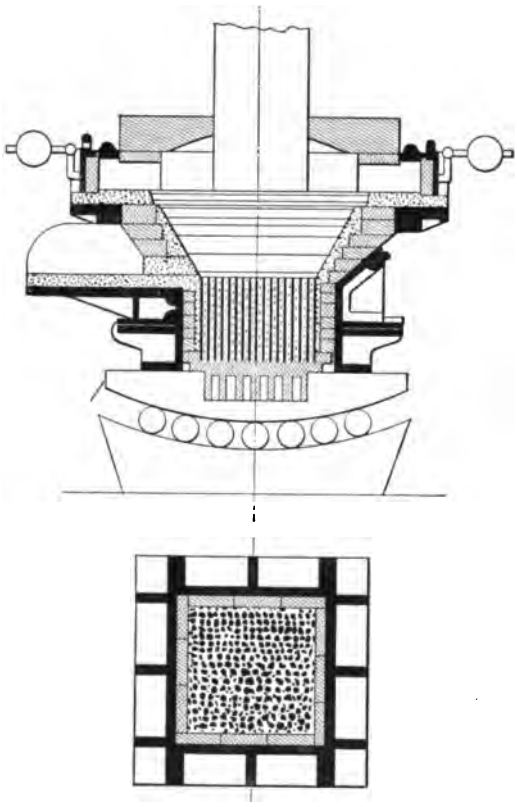


FIG. 114.

seen in the illustration this bottom consists of a water-cooled iron plate over the whole surface of which are set a number of evenly distributed iron rods from one inch to 1.18″ in diameter, between which magnesite is rammed. This is, in itself, a fairly good conductor. In this way a semi-refractory bottom is formed

with a conduction between that of iron and magnesite. According to Keller's results such a bottom is practically unmeltable. It is questionable whether his electrode arrangement offers any advantage over that of Girod. It depends on the durability of the furnace hearth in the two cases concerning which only work under practically the same conditions can give conclusions. The production of heat in the two furnaces is in no way influenced by the bottom electrodes. The uniform composition of the

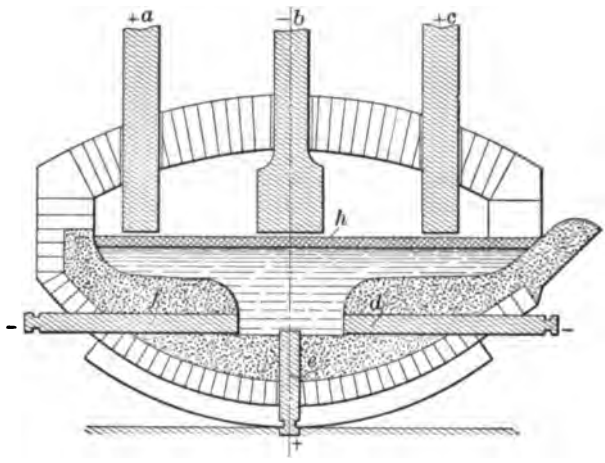



FIG. 115.

whole furnace bottom in the case of the Keller furnace will not bring about the profitable circulation of the bath found in the Girod furnace.

In this case also the original Girod is to be preferred to the newer Keller furnace, provided that the bottom will last as long in the first case as in the second.

Often one finds in the patent papers the endeavor to increase the resistance of the bath by means of a suitable shape of hearth, and so bring about an additional resistance heating. As an example, the *Nathusius* furnace may be mentioned. Fig. 115 gives a section of this furnace taken from the patent papers. It shows a number of electrodes of changeable polarity arranged

above and below the melted material. In this way the current can be forced to flow through and around the molten bath. According to the description given with the drawing, the current flows first from the upper middle electrode *b* through the slag covering *h* and the upper layers of the metal bath to the upper outer electrodes *a* and *c*, second from the lower middle electrode *e* to the lower outer electrodes *d* and *f*. In addition, however, the current ought to travel from the outer upper electrodes *a* and *c* to the outer lower steel electrodes *d* and *f*, so that the bath will be enclosed by heat-producing currents.

The whole arrangement, as is immediately apparent, represents a combination of the Héroult and Girod furnaces. In the

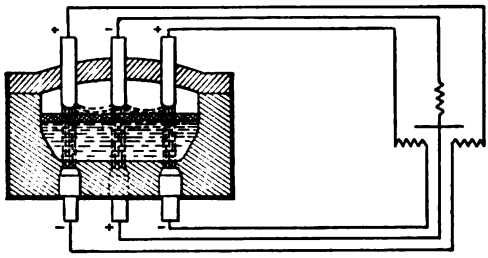


FIG. 116.

first place it is presumed that it is possible to heat the bath by current led in through electrodes which have a much smaller section than that of the bath. This is naturally altogether impossible if the electrodes consist of carbon, as is the case with those arranged over the bath, which has an excessively high resistance in comparison with the fluid metal. In addition it can be shown that it is impossible to bring about much heating by means of the water-cooled electrodes, for their section in proportion to the bath is so small that the higher specific resistance of the bath can have no important influence. Fig. 116 shows the practical arrangement of a *Nathusius* furnace that differs from the drawing in the patent papers because of a simpler and therefore better form of hearth. Here a direct heating of the bath, by means of the bottom electrodes, is not

taken into consideration because of the greatly increased section. The arrangement of the water-cooled electrodes in the latest furnaces differs from Fig. 115, and according to *Neumann's* report in *Stahl und Eisen*, 1910, they have a diameter of 8.66″, and are covered with a layer of dolomite 7.87″ thick. With the passage of the current this layer gives off heat, and so much as is not carried away through the bottom electrodes enters the bath. For increasing this bottom heating an additional 150 kw. transformer is used for a 5-ton furnace. Currents of a maximum of 6000 to 8000 amperes are used, that enter the bath from each carbon electrode, when a three phase 110 volt current is employed amounting to about 2500 amperes. The direct heating of a metal bath 11.8″ deep and about 78.74″ diameter is altogether impossible with these currents. It is therefore also impossible with the present arrangement of the furnace to use the bottom heating alone, although this is advanced as a special advantage of the furnace in question.

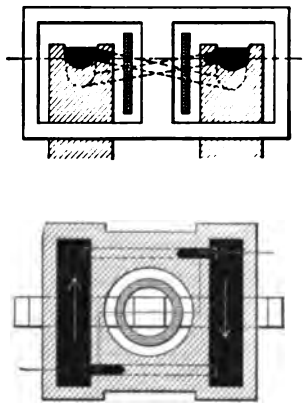


FIG. 117.

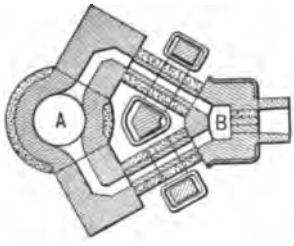



FIG. 118.

After all, the small advantage that the bottom heating may bring about must be looked upon as dearly purchased when it is considered that the *Nathusius* furnace shows a much more complicated construction than the Héroult or Girod alone, and uses practically the same method of heating. Moreover, it has more electrodes than the simpler older furnaces and therefore has greater heat losses. In addition six conductors are used for the current as compared with three

for the Héroult furnace. Apart from this the method of construction does not appear as good as that of either the Héroult or Girod furnaces.

In the sphere of induction furnaces the constant endeavor appears to be the production of greater movement in the bath of metal. Most of the proposals show an ignorance of the principles of the induction furnace, for otherwise the designers would know that in these furnaces a completely satisfactory mixing of the whole molten material is produced by the electric

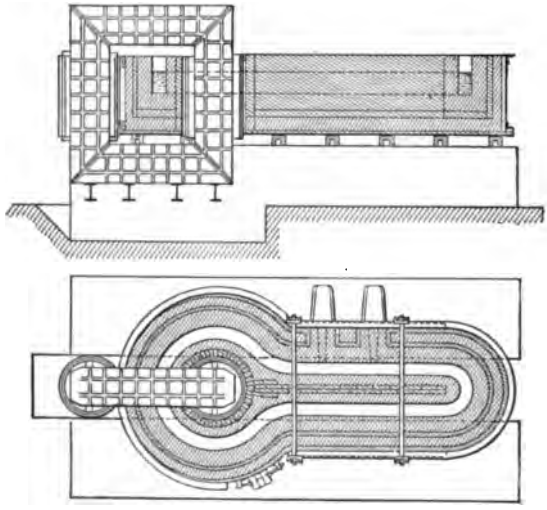


FIG. 119.

and magnetic conditions themselves. We can, therefore, leave out of consideration all the proposed furnaces that make use of inclined channels of small section through which the hotter material ought to rise, while the colder should descend. Such an arrangement proposed by Gin is shown in Fig. 117.

The Schneider-Creusot induction furnace, of which a section is given in Fig. 118, is worthy of notice. This furnace, however, has not been improved since it was first designed. Like the Gin furnace mentioned above, and which appeared much later, it shows an induction channel with several hearth-like widenings.

All such constructions of induction furnaces have the disadvantage that extremely high temperatures must be produced in the narrow channels if the material in the hearths is to be kept hot enough. This brings about a very energetic attack on the lining at these places, and as a result high maintenance costs and frequent delays in the working of the furnace with the Schneider-Creusot furnace refining is only carried out in the hearth *A*, and the remaining metal is kept free from slag. The use of the small hearth *B* is therefore not apparent. The arrangement of the furnace cannot be called simple. With this furnace also great value is laid on the increase of movement in the bath due to the great differences in section, and this appears reasonable. For obtaining this circulation the furnace is built on three columns, two of which allow a rise or fall in the furnace, so that during the operation the heating channels or pipes can be inclined at a sharp angle.

The furnace at the Creusot Works is arranged for a one-ton charge.

Other types of induction furnaces endeavor to increase the resistance of the bath, and so bring about an improvement in the power factor. The proposal of *Grönwall*, which is shown in Fig. 119, may serve as an example. We see here the ordinary channel of the induction furnace, greatly elongated on one side. This arrangement naturally brings about a considerable increase in the resistance of the bath, but it has the disadvantage of causing very great radiation losses. Further, it is impossible, according to metallurgical practise, to maintain the division wall that is necessary between the two parallel parts of the hearth, because no refractory material is known that will resist an intense heating from both sides. Further, it may be mentioned that such a furnace can only be used for the melting of pure materials, for work with slags cannot be carried out even to the small extent possible in the purely ring-shaped furnaces. This proposal, also, has not yet passed the experimental stage.

Roberston, in the November, 1911, issue of the *Metallurgical and Chemical Engineering*, writes of the Grönwall two phase arc furnace. This furnace is the invention of Grönwall, Lindblad

& Stalhane. Having originally worked with various types of induction furnaces without great success they decided to design an arc furnace. This furnace operates with two phase current, having two vertical carbons passing through the roof, each one to a phase. See Fig. 119*a*. The current arcs from the electrodes to the charge, passing through this and then through the basic lining at the centre of the hearth bottom, to the neutral return which is a carbon block fixed in the bottom of the furnace. The top of this bottom electrode comes level with the brickwork so that it does not project into or in any way weaken the basic lining. The hearth of the furnace therefore is not broken by any projections. The furnace has three doors, one at each end and one at the spout. Either hand or automatic regulation is provided for the electrodes. This furnace is of the tilting variety, being mounted in curved rails. Heat regulation is obtained by varying the voltage of a special regulating transformer. The normal working voltage is 65.

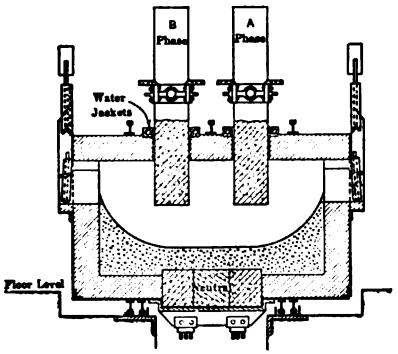



FIG. 119*a*.

As each phase of a two phase circuit is connected to one of the vertical electrodes the arcs are independently formed, so that if one arc is broken the other remains. This insures steadier running than if both arcs were in series as in the Héroult furnace. The arrangement of two arcs operating in parallel with a ne tral return through the bottom produces a vertical as well as a horizontal circulation in the metal bath, slightly different from that in a Girod furnace.

Naturally there have been many attempts to combine the various types, such as the induction and arc furnace. Fig. 120 shows one, and is that of *Hiorth*. (Such proposals originated at the time when the causes for the failure of the channel-shaped

induction furnaces for refining purposes were not clearly known, and it was thought that the slag temperature was not high enough. In the meantime the successful operation of the Röchling-Rodenhauser furnaces has shown the incorrectness of this reasoning.) In Fig. 120 we see the channel of an induction furnace broken by a division wall, which is bridged by a stirrup-shaped electrode. This electrode should only just touch in the slag, and bring it to a very high temperature. This shows a complete ignorance of the probabilities. The unmistakable result of the proposed method of working would be a complete freezing up of the metal in the channel on the opposite sides of the electrodes. It would be impossible to introduce sufficient current into the bath through the electrode, with which to produce heat enough, by overcoming the bath resistance, to keep the metal fluid.

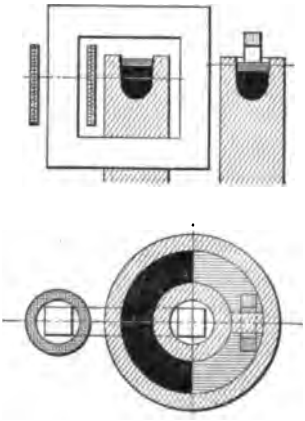


FIG. 120.

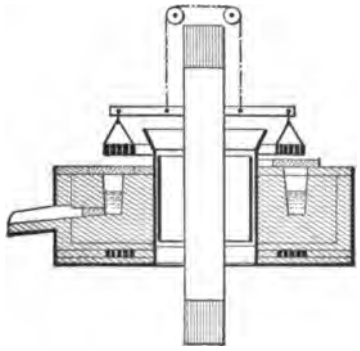


FIG. 121.

Even so, *Hiorth* says that he does not consider this furnace construction to be valueless, still we do not find that he has used this method in the single commercial furnace which he has constructed, which is shown in side elevation by Fig. 121. This is a purely induction type of furnace with the primary winding in flat spools similar to the arrangement already proposed by *de Ferranti* and later again by *Frick*, excepting that *Hiorth* coils

both legs of the magnet. The coils, according to a paper read by Dr. Jos. W. Richards before the American Electrochemical Society, in 1910, are uninsulated copper coils, hollow and the lower ones water-cooled. The construction of the furnace is such that it may be tilted independently of the magnet.

So far, Richards continues, *Hiorth* uses his furnace only for melting the purest obtainable Swedish Dannemora pig iron and Dannemora Walloon iron. Yellowish-white blast-furnace slag was being used as a flux. The contents of the furnace being 5 tons, 3 tons were poured at a time and 2 tons left in to start the next charge. The details of a heat run-off are then given which are here omitted. We quote further:

(Assuming 300 calories necessary to melt 1 kg. of steel the thermal efficiency of this melting operation is 55% and the furnace radiation loss calculates out 180 kw. at this temperature. It was stated that it took about 170 kw. to keep the charge melted when the furnace was kept up to heat over night.)

The power factor varied from .80 at the beginning of the run to .57% at the end when the metal in furnace was 5.77 tons and at casting temperature. Current used averaged 395 kw. for 6 hours or 790 kw. hours per ton of steel. As low as 700 kw. hours has been reached in this 5-ton furnace on cold materials. This furnace operates at 12½ cycles, 400 to 500 kw. at 250 volts single phase.

Other proposals consist usually of combinations that in most cases would bring about great difficulties in operation, and which offer no advantages over the original furnaces. Here belong those which take an ordinary metallurgical furnace, such as an open hearth, and operate it at certain times by a stoppage of the gas, and the use of carbon electrodes. Also a combination of converter and electric furnace, for instance a small converter with an arc furnace built in. With these combinations the conditions of operation have not been considered carefully enough. For instance an open-hearth furnace in comparison with an electric furnace has such a high roof, and large working surface of bath, that the heat losses when using carbon electrodes, even if only for the desulphurizing period, would bring about

much too high costs. In these cases it is therefore much better to transfer the charge from the open-hearth furnace, or the Bessemer, to a special electric furnace by means of a casting ladle, and to stand the unavoidable heat losses. In this way cheaper and better results will be obtained than with any of the proposals mentioned above, none of which has been really seriously tried out up to the present.

This book would not seem complete if mention were not made of the *Baily* resistance furnace for heating bars, billets, and ingots.

The first experimental work, leading to the successful development of the present type of resistance furnace for reheating steel,

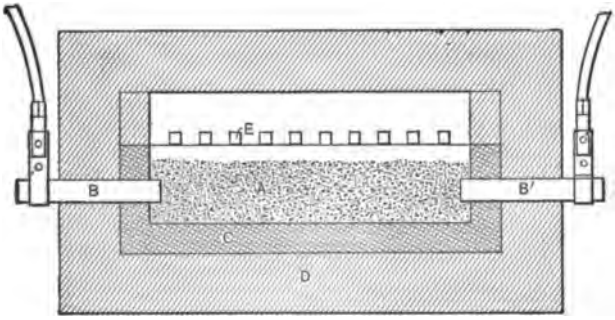



FIG. 121*a*.

was done in 1906 at the plant of the Transue & Williams Company, Alliance, Ohio, and although subsequent work at this plant showed that electric furnaces for heating bars was feasible, the management of the plant was not satisfied by the cost of operation, owing to their lack of economically developing power. In the fall of 1911 Thaddeus Baily, of Alliance, Ohio, built at that place an experimental laboratory and demonstration plant of 200 kw. capacity, and after some months of careful work built a furnace that has all the requirements necessary for a commercial electric furnace for the purpose of heating steel for forgings.

The latest type of this furnace for heating bars and small billets for forging operations as shown in Fig. 121*a* may be

briefly described as follows: In the bottom of the rectangular fire-brick enclosure *D* is located the resistance material *A* composed of crushed coke; the bottom of the furnace is protected by a lining of high-grade magnesite material *C*, which will not flux with carbon, even at the high temperature of the electric furnace; the current is conducted through the furnace walls by means of graphite electrodes *B–B*, making contact with the resistance material or core immediately inside the furnace chamber; the heat given off from the core *A* heats the bars *E* lying immediately above it and in the same chamber, and which are supported by a ledge at the back of the furnace, as shown in Fig. 121*b*. As the metal and the resistance material are in the same chamber, the slight formation of CO from the coke keeps the heating chamber under a reducing atmosphere, and there is *no loss of metal by oxidation, and hence no scale forms while the metal is in the furnace.* No coal, gas, or oil fired furnace for heating bars or billets has this advantage.

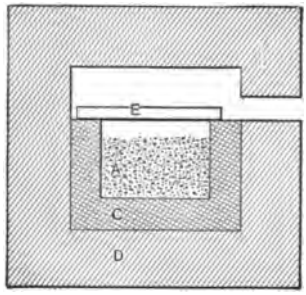



FIG. 121*b*.

The furnace is controlled by means of voltage change, the usual range required being two to one, and is performed by means of a special regulating transformer and dial switch, an increase in voltage making a proportioned increase in current flow, the input in kilowatts increasing as the square of the voltage, within usual operating limits.

This type of furnace is ideal from an electrical standpoint, as the operating voltages are moderate, seldom exceeding 110 volts, and the power factor even in 60 cycle circuits is extremely high (seldom less than 98 per cent.) on account of the load being practically non-inductive.

The temperature range and control are all that could be desired, as any temperature may be obtained and maintained, that is, within the limit of the refractory materials used for the construction of the furnace.

Temperatures of 1750° C. in the furnace chamber have been readily maintained for long periods without other trouble than that due to the roof and walls of the furnace, which in this case were of silica and softened at the temperature named.

As the temperature is proportioned to the input of electricity in kilowatts, the control of temperature through the current regulating device described above is extremely simple and accurate, and when the furnace is once heated until the walls have reached an equilibrium the loss of heat becomes constant and may be reckoned in a definite number of kws. per hour, for any given temperature. With a definite weight of steel, being heated per hour to a certain temperature, requiring a known number of kw. hours, the voltage may be adjusted to give this required kw. input, and in such cases the temperature of the furnace cannot vary.

With an increase or decrease of heating capacity of the furnace, the voltage and kw. input may be readily changed to maintain the desired temperature.

| | |
|---|---|
| Temperature of interior at charging | 2615° F. (1435° C.) |
| Temperature of interior at withdrawing | 2600° F. (1426° C.) |
| Voltage of furnace | 52 |
| Amperage of furnace | 1000 |
| Power factor | 0.99 |
| Indicated kilowatts | 52 |
| Amount of metal charged, being 8 bars 1½ in. (3.8 cm.) square by 18 in. (45 cm.) long | 92 pounds (41.7 kg.) |
| Time in furnace | 20 minutes |
| Temperature of metal, when charged | 60° F. (15° C.) |
| Temperature of metal, when withdrawn | 2360° F. (1239° C.) |
| Kilowatt hours consumed in heating metal | 17 |
| Pounds (kg.) of metal per kilowatt hour | 5 pounds (2.25 kg.) |
| Kilowatt hours per gross ton of metal heated | 440 |
| Capacity of furnace, per hour | 276 pounds (125 kg.) |

A typical operating performance on a 60 kw. furnace heating slightly over 3 tons daily, or 135 kg. (300 lb.) of steel per hour, is given above; the table, showing a rate of metal heated per unit of current consumption of 2.25 kg. (5 lb.) per kw. hour or 440 kw. hours per ton, with steel heated to 1300° C. and

requiring 220 calories per kg. (400 B. T. U. per pound). These figures show a thermal efficiency of 67 per cent.

The following list shows the furnaces of the type described that are either in operation or building:

| Names of Plants. | Place. | Number of Furnaces. | Size. | Capacity per Hour. |
|---|---|---|---|---|
| Canton Drop Forge Co.. | Canton, Ohio..... | 2 | 60 kw. | 300 lb. 135 kg. |
| J. H. Williams Co..... | Brooklyn, N. Y..... | 1 | 50 " | 200 " 90 " |
| McKinnon Dash Co. ... | St. Catherines, Ont., Can. | 1 | 40 " | 150 " 70 " |
| Transue & Williams Co. | Alliance, Ohio..... | 1 | 60 " | 300 " 135 " |
| Electric Furnace Co.... | Alliance, Ohio..... | 1 | 40 " | 150 " 70 " |

The Baily furnace is manufactured and sold by *The Electric Furnace Co.* of *Alliance, Ohio.*

As a conclusion to this review, which is believed to embrace the most valuable proposals in the different spheres, it may be established that, until the invention of further types of construction, we have only to deal with those described in detail in the special chapters. These furnaces still show many weaknesses in comparison with the ideal furnace, yet they show that in those with the greatest simplicity the ideal has been closely approached.

# CHAPTER XV

## FINAL CONSIDERATIONS

THE purely technical side of the application of electric furnaces to the iron and steel industry has been considered in the foregoing chapters, so that now something may be said with regard to the economical questions of electric heating.*

We have seen already in Chapter I that the development of electric furnaces is closely connected with that of electro-technology. This is still the case when the question as to whether the installation of an electric furnace under certain conditions will be an economic success or not is under discussion. Then, indeed, the cost of the electric current, which is the heating agent of the electric furnace, is of real influence for the success of an electric steel plant. It must be taken into consideration that electricity, in by far the most cases, is much more expensive than the ordinary methods of heating, nevertheless this disadvantage is more than equalized by other advantages.

In this connection we may quote from Borchers' address before the *Verein Deutscher Eisenhüttenleute*, in 1905. "If we reckon the kilogram of carbon in coke at a high price, say about 0.714c., then 1000 kg. calories will cost 0.088c. Very cheap electric power, namely at $9.52 per h.p. year, gives 1000 kg. calories from 0.167c. to 0.214c. according to the number of working days. This disadvantage of electric heat production is balanced by this condition; that the material to be heated, which in this case is the charge itself, accomplishes partly or altogether the transformation of the electric energy into heat. In a certain way it forms, of itself, the source of heat, while in all combustion furnaces the heat goes first to a mixture of gases, and from this to the material to be smelted."

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* For a more detailed discussion see Part II under "Costs of Operation."

In the above example the price of power taken is very cheap, for with $9.52 per h.p. year, and assuming 300 working days in the year, the kw. hour only costs 0.178c. Such a low figure is only to be reached with the use of very suitable water-powers, while it is unattainable by using blast-furnace gas, provided that the blast-furnace gas is reckoned at a cost corresponding to its heating value. If this is done then it will usually happen that, even with the use of large gas-engines, the kw. hour cannot be furnished lower than 0.357c. to 0.714c. Still more unfavorable are the results if steam is used, although here, also, progressive engineering has brought about a constant cheapening in the price of current. For instance, in well-conducted central stations, with the use of large steam turbines, it has been found possible to produce the kw. hour at about 0.714c., when the coal does not cost more than 0.41c. per kw. hour. This is, of course, provided that the demand for power is very uniform, and free from variation, for otherwise the price per kw. hour is increased considerably. In this connection von Rizzo, in the *Electrotechnische Zeitschrift*, p. 596, 1910, gives a figure of 1.31c., the power being produced by steam, and being used for operating a railroad with a very variable load.

The prices given have reference, almost always, to large central stations, such as large iron and steel plants, city stations, etc. With smaller producing plants the price of current naturally rises considerably. It is therefore recommended that small plants should almost always be connected to some large central station for their electric furnace power, if the opportunity is there. Such stations today often furnish power for 0.942c. to 1.428c. per kw. hour, which is a price that cannot be realized in small power stations, except with high pressure internal combustion oil engines.

We see then that the source of power used for the production of electricity can affect the price of current, and therefore the production costs of electric steel. Also the way the current is used plays a very important part, and this depends in the first instance on the method of working. The following table shows how this method of working influences the power consumption:

It requires for the production of:

| | | |
|---|---|---|
| Pig iron, direct from ore | 2,000 | Kw. Hrs. |
| Steel, direct from ore | 3,000 | " |
| Steel from cold pig iron | 1,500 | " |
| Steel from fluid pig iron | 1,000–1,200 | " |
| Steel from cold pig iron and cold scrap | 900–1,300 | " |
| Steel from molten pig iron and cold scrap | 600–1,000 | " |
| Steel from cold scrap | 600–900 | " |
| Refining of molten low carbon steel to make special quality steel (with very complete chemical purification) crucible steel quality | 200–300 | " |
| Refining of molten low carbon steel to ordinary electric steel (electric rails) | 120 | " |
| Retaining pig iron molten for foundry purposes (heated mixer) | 50 | " |

These values can naturally only serve as rough estimates, because the composition of the charge and the finished material are absolutely necessary for more exact figures. Further, more or less power will be used according to the efficiency of one or the other furnace, so that with the same charge and finished product different power-consumption figures will be given by two furnaces of different types.

The wide limits given for working mixtures of pig iron and scrap are necessary because the power consumption is greatly dependent on the percentage of pig iron and of scrap used, more being necessary with an increase of pig iron. Further details on these points are given in the second part of the book.

From what has been said it is apparent that the price of current becomes more of a determining factor (for the efficiency or non-efficiency of electric furnace operation), according to how many of the metallurgical processes necessary for changing ore to steel are carried out in the electric furnace. For instance, when fluid metal from a converter or open-hearth furnace is worked the cost for power, with an average unit price (0.476c. to 0.714c. per kw. hour), is about 3% of the production cost; but it increases to 12% with the same price per unit, when scrap is worked.

Finally we must remember that all of the furnaces in use

today have certain special advantages. Unfortunately each type of furnace has also certain disadvantages. These disadvantages are so closely connected with the methods of heating, that they must be allowed for. If electric steel production is entered into today one of the existing furnaces must be chosen, and its advantages and disadvantages purchased together. It is therefore not without interest to see how widely distributed the various types have become up to date. The following statistical tables date up to 1913.

The tables show that the more important furnace types have already become so wide-spread that they must be considered to have passed the experimental stage. At the same time the electric furnace has shown that it is of considerable economic importance because *it has enabled the production of the very best finished steel from low priced material.* Until now the purest and therefore the dearest raw materials were necessary for this purpose. The tables clearly show that this great economic advantage of the electric furnace is becoming known more and more.

When we realize that the Stassano, Héroult, and Kjellin furnaces were first brought out in 1900, and the Girod and Röchling-Rodenhauser in 1906 and 1907, the wide-spread distribution of these furnaces takes on greater importance. How quickly this distribution increases is also shown by the table, for in addition to 131 furnaces now in operation, 14 are under construction.

It may be concluded by pointing out that the electric furnace is already firmly established in the iron and steel industry, that the present development of electric furnace plants has been very rapid, and that an important future is assured.

## (a) ARC FURNACES

| Type | No. | Firm | With Metric Tons Charge | | | Current | Kw. Used | Kind of Charge | Use of Product |
|---|---|---|---|---|---|---|---|---|---|
| | | | In Use | Not Running | Building | | | | |
| Héroult..... | 1 | Steel plant R. Lindenberg A. G. Remschied, Hasten, Germany. | 1.8 | ..... | ..... | Single phase | 400 | Molten metal from OH, occasionally cold metal. | Tool steel, structural, war material. |
| Héroult..... | 2 | Steel plant R. Lindenberg A. G. Remschied, Hasten, Germany. | 3. | ..... | ..... | Single phase | 520 | Molten metal from OH, occasionally cold metal. | Tool steel, structural, war material. |
| Héroult..... | 3 | Bismarckütte, Upper Silesia, Germany. | 1. | ..... | ..... | Single phase | 400 | Molten metal from OH, occasionally cold metal. | War material, high, silicon, dynamo steel, locomotive tires. |
| Héroult..... | 4 | Bismarckhütte, Upper Silesia, Germany. | 3. | ..... | ..... | Single phase | 540 | Molten metal from OH, occasionally cold metal. | War material, high silicon, dynamo steel, locomotive tires. |
| Héroult..... | 5 | Mannesmann tube works, Burback, Germany. | 3. | ..... | ..... | Single phase | 570 | Molten metal from OH, occasionally cold metal. | Seamless tubes, castings. |

## (a) ARC FURNACES (*Continued*)

| Type | No. | Firm | With Metric Tons Charge | | | Current | Kw. Used | Kind of Charge | Use of Product |
|---|---|---|---|---|---|---|---|---|---|
| | | | In Use | Not Running | Building | | | | |
| Héroult..... | 6 | "Deutscher Kaiser" Bruckhausen, Germany. | 6. | ..... | ..... | Single phase | 800 | Cold material and liquid OH steel. | Seamless tubes, rails, ordinary qualities. |
| Héroult..... | 7 | "Deutscher Kaiser" Bruckhausen, Germany. | 6. | ..... | ..... | Single phase | 800 | Cold material and liquid OH steel. | Seamless tubes, rails, ordinary qualities. |
| Héroult..... | 8 | "Deutscher Kaiser" Bruckhausen, Germany. | ..... | ..... | 25 | Three phase 50 cycles | 1850* | Hot metal. | ? |
| Héroult..... | 9 | Gebr. Böhler & Co., Kapfenberg, Austria. | 2.5 | ..... | ..... | Single phase | 400 | Cold material and liquid OH steel. | All kinds tool steel, structural war material. |
| Héroult..... | 10 | Kärtnerische Eisen & Stahlwerksgesellschaft, Ferlach, Austria. | 5.0 | ..... | ..... | Single phase | 765 | Cold charge. | Wire rods. |
| Héroult..... | 11 | Lapp Bros., Rottenmann, Austria. | 6. | ..... | ..... | Single phase | 785 | Cold charge. | Dynamo, die steel and fine plate castings. |
| Héroult..... | 12 | Gg. Fischer, Schaffhausen, Switzerland. | 1.2 | ..... | ..... | Single phase | 250 | Cold charge. | Castings. |

*This furnace was designed to take 3000 to 3500 kw., but 1850 kw. is the maximum that can be forced into it. The high frequency no doubt affects it.

| Type | No. | Firm | With Metric Tons Charge | | | Current | Kw. Used | Kind of Charge | Use of Product |
|---|---|---|---|---|---|---|---|---|---|
| | | | In Use | Not Running | Building | | | | |
| Héroult ..... | 13 | Società Tubi Mannesmann, Dalmine, Italy. | 6. | ..... | ..... | Single phase | 765 | Cold charge. | Seamless tubes. |
| Héroult..... | 14 | Società Tubi Mannesmann, Dalmine, Italy | 6. | ..... | ..... | Single phase | 765 | Cold charge. | Seamless tubes. |
| Héroult ..... | 15 | Soc. Electrométallurgique, Française, Froges, France. | 2.50 | ..... | ..... | Single phase | 400 | Cold charge. | Tool steel. |
| Héroult..... | 16 | Aciéries du Saut du Tarn, St. Juéry, Fr'ce | 5. | ..... | ..... | Single phase | 500 | Liquid open hearth metal. | Tool steel. |
| Héroult..... | 17 | Usines Métallurgiques du Hainaut, Couillet, Belgium. | 5. | ..... | ..... | Single phase | 400 | Liquid open hearth metal. | Castings. |
| Héroult..... | 18 | John Allen & Co., Sheffield, Eng. | 2.5 | ..... | ..... | Single phase | 400 | Liquid open hearth metal. | Tool steel. |
| Héroult..... | 19 | Vickers, Son & Maxim, Sheffield, Eng. | 2.5 | | | | | | |
| Héroult..... | 20 | Obuchowsche Stahlwerke, St. Petersb'g. | 3.5 | ..... | ..... | Single phase | 660 | Liquid open hearth metal. | Marine material. |
| Héroult..... | 21 | Aktiebolaget Héroult Electriska Stal, Kortfors, Sweden. | 3.5 | ..... | ..... | Single phase | 400 | Cold charge | Tool Steel |
| Héroult..... | 22 | Halcomb & Co., Syracuse, N. Y., U. S. A. | 5. | ..... | ..... | Single phase | ..... | Molten pig iron and OH mtl. | Tool steel. |

## (a) ARC FURNACES (*Continued*)

| Type | No. | Firm | With Metric Tons Charge | | | Current | Kw. Used | Kind of Charge | Use of Product |
|---|---|---|---|---|---|---|---|---|---|
| | | | In Use | Not Running | Building | | | | |
| Héroult..... | 23 | Firth Sterling Steel Co., McKeesport, Pa., U. S. A. | 2.5 | ..... | ..... | Single phase | ..... | Liquid open hearth steel. | Tool steel. |
| Héroult..... | 24 | Firth Sterling Steel Co., McKeesport, Pa. | 5. | ..... | ..... | Single phase | ..... | Liquid open hearth steel. | Tool steel. |
| Héroult..... | 25 | Illinois Steel Co., So. Chicago, Ill., U.S.A. | 15. | ..... | ..... | Three phase | 2,000 | Liquid Bessemer steel. | Rails and railroad material. |
| Héroult..... | 26 | American Steel & Wire Co., Worcester, Mass., U. S. A. | ..... | 15. | ..... | Three phase | 2,000 | Liquid Bessemer steel. | Wire rod. |
| Héroult..... | 27 | Electro - Metals Ltd., Welland, Canada. | ..... | .5 | ..... | ..... | ..... | ..... | Ferro-alloys. |
| Héroult..... | 28 | Electro - Metals Ltd., Welland, Canada. | ..... | 5. | ..... | ..... | ..... | ..... | Ferro-alloys. |
| Héroult..... | 29 | Co. Mexicana de Aceros y Chimicos, Mexico | 4. | ..... | ..... | ..... | ..... | ..... | ..... |
| Héroult..... | 29 | Co. Mexicana de Aceros y Chimicos, Mexico | 4. | ..... | ..... | ..... | ..... | ..... | ..... |
| Héroult..... | 31 | Natl. Malleable Castings Co., Sharon, Pa., U. S. A. | 3 | ..... | ..... | Single phase | 450 | Hot charge. | Castings. |

| Type | No. | Firm | With Metric Tons Charge | | | Current | Kw. Used | Kind of Charge | Use of Product |
|---|---|---|---|---|---|---|---|---|---|
| | | | In Use | Not Running | Building | | | | |
| Girod..... | 1 | Cie des Forges et Aciéries Electriques Paul Girod, Ugine, France. | 1.8 | ..... | ..... | Single phase | 300 | Cold charge. | Ordinary and special steels, castings. |
| Girod..... | 2 | Cie des Forges et Aciéries Electriques Paul Girod, Ugine, France. | 2.0 to 2.25 | ..... | ..... | Single phase | 300 to 400 | Cold charge. | Ordinary and special steels, castings. |
| Girod..... | 3 | Cie des Forges et Aciéries Electriques Paul Girod, Ugine, France. | 2.0 to 3. | ..... | ..... | Single phase | 300 to 400 | Cold charge. | Ordinary and special steels, castings. |
| Girod..... | 4 | Cie des Forges et Aciéries Electriques Paul Girod, Ugine, France. | 2.0 to 3. | ..... | ..... | Single phase | 300 to 400 | Cold charge. | Ordinary and special steels, castings. |
| Girod..... | 5 | Cie des Forges et Aciéries Electriques Paul Girod, Ugine, France. | 8.0 to 12.5 | ..... | ..... | Three phase with four electrodes | 1,200 | Cold charge. | Ordinary and special steels, castings. |
| Girod..... | 6 | Cie des Forges et Aciéries Electriques Paul Girod, Ugine, France. | 8.0 to 12.5 | ..... | ..... | Three phase with four electrodes | 1,200 | Cold charge. | Ordinary and special steels, castings. |

## (a) ARC FURNACES (*Continued*)

| Type | No. | Firm | With Metric Tons Charge | | | Current | Kw. Used | Kind of Charge | Use of Product |
|---|---|---|---|---|---|---|---|---|---|
| | | | In Use | Not Running | Building | | | | |
| Girod..... | 7 | Marrel Frères, Rive de Gier, France. | 5. | ..... | ..... | Single phase | 600 | Cold and liquid charge. | ..... |
| Girod..... | 8 | Oehler & Co., Aarau, Switzerland. | 2.0 | ..... | ..... | Single phase | 300 | Cold and liquid charge. | Castings. |
| Girod..... | 9 | Soc. John Cockerill, Seraing, Belgium. | 3. to 4.0 | ..... | ..... | Single phase | 450 | Cold and liquid charge. | Ordinary and special steels. |
| Girod..... | 10 | A. Stotz, Stuttgart-Korn-Westheim, Germany. | 1.0 | ..... | ..... | Single phase | 300 | Cold charge. | Castings. |
| Girod..... | 11 | Gutchoffnungshütte, Oberhausen, Germ. | 2. to 3. | ..... | ..... | Single phase | 300 to 400 | Cold and liquid charge. | Special quality steels. |
| Girod..... | 12 | Stalwerke Becker, Krefeld, Germany. | 2. to 3. | ..... | ..... | Single phase | 300 to 400 | Cold and liquid charge. | Special quality steels. |
| Girod..... | 13 | Fried. Krupp A.-G. Essen, a R., Germ. | 10. to 12. | ..... | ..... | Single phase | ..... | Cold and liquid charge. | Special quality steels. |
| Girod..... | 14 | TernitzerEisen&Stahlwerke, Schoeller & Co., Terniz, Austria. | .5 | ..... | ..... | Single phase alternating | ..... | Cold and liquid charge. | Tool steel and special quality steels. |
| Girod..... | 15 | Danner & Co., Judenburg, Austria. | 1.8 to 2. | ..... | ..... | Single phase | 300 | Cold charge. | Special quality steels. |

| Type | No. | Firm | With Metric Tons Charge | | | Current | Kw. Used | Kind of Charge | Use of Product |
|---|---|---|---|---|---|---|---|---|---|
| | | | In Use | Not Running | Building | | | | |
| Girod..... | 16 | Diosgyörer Kgl. Eisen & Stahlwerke, Diosgyör, Hungary. | 2. | ..... | ..... | Single phase | 300 | Cold charge. | Special quality steels. |
| Girod..... | 17 | Simonds Mfg. Co., Lockport, N. Y., U. S. A. | 1. | ..... | ..... | Single phase | 200 | Cold charge. | Tool steel. |
| Girod..... | 18 | Bethlehem Steel Co., So. Bethlehem, Pa., U. S. A. | ..... | ..... | 10 | ..... | ..... | ? | Tool steel. |
| Girod..... | 19 | Rubery Owen & Co., Darlarston, England | ..... | ..... | 3. | Single phase | ..... | ? | ? |
| Stassano..... | 1 | Dunston-on-the-Tyne, Steel Works. | ..... | ..... | 1. | Three phase | 200 | Cold. | ? |
| Stassano..... | 2 | Royal Arsenal, Turin, Italy. | 0.8 | ..... | ..... | Three phase | 150 | Cold scrap. | War material. |
| Stassano..... | 3 | Royal Arsenal, Turin, Italy. | 0.8 | ..... | ..... | Three phase | 150 | Cold scrap. | War material. |
| Stassano..... | 4 | Rheinische Electro-stahlwerke G. m. b. H., Bonn. | 1.5 | ..... | ..... | Three phase | 260 | Cold scrap. | Castings and tool steel. |
| Stassano..... | 5 | Rheinische Electro-stahlwerke G. m. b. H., Bonn. | 1.5 | ..... | ..... | Three phase | 260 | Cold scrap. | Castings and tool steel. |

## (a) ARC FURNACES (*Continued*)

| Type | No. | Firm | With Metric Tons Charge | | | Current | Kw. Used | Kind of Charge | Use of Product |
|---|---|---|---|---|---|---|---|---|---|
| | | | In Use | Not Running | Building | | | | |
| Stassano..... | 6 | Leopold Gasser St. Pölten, Vienna. | 1. | ..... | ..... | Three phase alternating | 200 | Cold scrap. | Castings, special quality steels. |
| Stassano..... | 7 | Leopold Gasser St. Pölten, Vienna. | 1. | ..... | ..... | Three phase alternating | 200 | Cold scrap. | Castings, special quality steels. |
| Stassano..... | 8 | Societa Elba, Porto Ferrario. | 1.2 | ..... | ..... | Three phase | 250 | ..... | ..... |
| Stassano..... | 9 | Societa Elba, Liguria. | ..... | ..... | 6.0 | Three phase | 800 | ..... | ..... |
| Stassano..... | 10 | Fonderia Milanesd'Acciaio. | 1.2 | ..... | ..... | Three phase | 250 | ..... | ..... |
| Stassano..... | 11 | Fonderia Milanesd'Acciaio. | .5 | ..... | ..... | Three phase | 100 | ..... | ..... |
| Stassano..... | 12 | Fonderia Milanesd'Acciaio. | .5 | ..... | ..... | Three phase | 100 | ..... | ..... |
| Stassano..... | 13 | J. J. Hoehn, Odessa, Russia. | 1.2 | ..... | ..... | Three phase | 250 | ..... | ..... |
| Stassano..... | 14 | J. J. Hoehn, Odessa, Russia. | 1.2 | ..... | ..... | Three phase | 250 | ..... | ..... |
| Stassano..... | 15 | Electro Flex Steel Co., Ltd., Newcastle-on-the-Tyne. | 1.2 | ..... | ..... | Three phase | 250 | ..... | ..... |
| Stassano..... | 16 | Electro Flex Steel Co., Ltd., Newcastle-on-the-Tyne. | 1.2 | ..... | ..... | Three phase | 250 | ..... | ..... |

| Type | No. | Firm | With Metric Tons Charge | | | Current | Kw. Used | Kind of Charge | Use of Product |
|---|---|---|---|---|---|---|---|---|---|
| | | | In Use | Not Running | Building | | | | |
| Stassano..... | 17 | Electro Flex Steel Co., Ltd., Newcastle-on-the-Tyne. | 1.2 | ..... | ..... | Three phase | 250 | ..... | ..... |
| Keller..... | 1 | Acieries J. Holtzer, Unieux, France. | 8. | ..... | ..... | Single phase alternating four electrodes groups of two | 750 | Fl'd open-hearth steel. | Special quality steels, war material. |
| Keller..... | 2 | Acieries J. Holtzer, Unieux, France. | 1.5 | ..... | ..... | Same current one electrode and conducting hearth electrode | 200 | Fl'd open-hearth steel and cold charge. | Special quality steels, war material and tool steel. |
| Keller..... | 3 | Société des Établissements Keller - Leleux, Livet, France. | 1.50 | ..... | ..... | Same current one electrode and conducting hearth electrode | 200 | Cold charge. | Castings special quality steels, special steels. |
| Keller..... | 4 | Société des Établissements Keller-Leleux, Livet, France. | 3.5 | ..... | ..... | Same current one electrode and conducting hearth electrode | 450 | Cold charge. | Castings special quality steels, special steels. |

## (a) ARC FURNACES (*Continued*)

| Type | No. | Firm | With Metric Tons Charge | | | Current | Kw. Used | Kind of Charge | Use of Product |
|---|---|---|---|---|---|---|---|---|---|
| | | | In Use | Not Running | Building | | | | |
| Keller..... | 5 | Société des Établissements Keller-Leleux, Livet, France. | 0.2 | ..... | ..... | Same current one electrode and conducting hearth electrode | 80 | Cold charge. | Experimental. |
| Keller..... | 6 | LuxemburgerBerwerks u.SaarbrückerEisenhütten Akt. Ges. Burbacherhütte, Saarbrucken, Germany. | 3.5 | ..... | ..... | Same current one electrode and conducting hearth electrode. | 450 | LiquidbasicBessemer steel. | Average qualities, rails, structural steels. |
| Chapelet..... | 1 | Soc. des Hauts Fourneaux et Forges, Allevard, France. | 3.5 | ..... | ..... | Single phase alternating | 340 | Cold charge. | Ordinary and special steels. |
| Chapelet..... | 2 | Soc. des Hauts Fourneaux et Forges, Allevard, France. | 3.5 | ..... | ..... | Single phase alternating | 340 | Cold charge. | Ordinary and special steels. |
| Chapelet..... | 3 | Soc. des Hauts Fourneaux et Forges, Allevard, France. | 5. | ..... | ..... | Single phase alternating | 600 | Cold charge. | Ordinary and special steels. |
| Chapelet..... | 4 | Soc. des Hauts Fourneaux et Forges, Allevard, France. | 5. | ..... | ..... | Single phase alternating | 600 | Cold charge. | Ordinary and special steels. |

| Type | No. | Firm | With Metric Tons Charge | | | Current | Kw. Used | Kind of Charge | Use of Product |
|---|---|---|---|---|---|---|---|---|---|
| | | | In Use | Not Running | Building | | | | |
| Chapelet..... | 5 | Soc. des Hauts Fourneaux et Forges, Allevard, France. | 5. | ..... | ..... | Single phase alternating | 600 | Cold charge. | Ordinary and special steels. |
| Aktiebologet Elektrometall Ludvika Swed. | 1 | Arvika, Sweden..... | 1.0 | ..... | ..... | Three phase alternating | 175 | Cold charge. | Castings. |
| Aktiebologet Elektrometall Ludvika Swed. | 2 | Hagfors, Sweden..... | 0.5 | ..... | ..... | Two phase alternating | 125 | Cold charge. | Machinery steels, etc. |
| Aktiebologet Elektrometall Ludvika Swed. | 3 | A. S. Norsk, Electrometall Norway. | 6. | ..... | ..... | Two phase alternating | 736 | Liquid pig iron from electric shaft furnace. | Machinery steels, etc. |
| Aktiebologet Elektrometall Ludvika Swed. | 4 | St. John del Rey Mining Co., Brazil. | 2.0 | ..... | ..... | Two phase alternating | 300 | Cold charge. | Machinery steels, etc. |
| Special System | 1 | A. Hickman, Staffordshire, England. | 0.3 | ..... | ..... | ..... | ..... | ..... | ..... |
| Special System | 1 | Soc. An. des Aciéries et Forges, Firminy, France. | 0.05 | ..... | ..... | ..... | ..... | ..... | Test furnace. |

## (a) ARC FURNACES (*Continued*)

| Type | No. | Firm | With Metric Tons Charge | | | Current | Kw. Used | Kind of Charge | Use of Product |
|---|---|---|---|---|---|---|---|---|---|
| | | | In Use | Not Running | Building | | | | |
| Special System | 1 | Scott Anderson, Sheffield, Eng. | 0.75 | ..... | ..... | ..... | ..... | ..... | ..... |
| Special System | 1 | Treadwell Engineering Co., Easton, Pa., U. S. A. | 1.6 | ..... | ..... | Three phase alternating Electro Metals Ltd. | 300 | Cold charge. | Castings. |
| Grönwall, Lindblad & Stalhane. | 1 | Söderfors, Sweden.... | 2. | ..... | ..... | Two phase alternating | 350 | ? | ? |
| Grönwall, Lindblad & Stalhane. | 2 | Sheffield, England.... | 2.5 | ..... | ..... | Two phase alternating | 350 | ? | ? |

## (b) INDUCTION FURNACES

"Systems of the Gesellschaft für Elektrostahlanlagen," Berlin.

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 1 Kjellin.... | 1 | Fried. Krupp A. G., Essen, Germany. | 8.5 | ..... | ..... | Single phase alternating | 750 | Cold charge. | Special quality steels. |
| 2 Kjellin.... | 2 | Oberschlesische Eisenindustrie A. G., Gleiwitz, Germany. | 1.5 | ..... | ..... | Single phase alternating | 180 | Cold charge. | Special quality steels. |

| Type | No. | Firm | With Metric Tons Charge | | | Current | Kw. Used | Kind of Charge | Use of Product |
|---|---|---|---|---|---|---|---|---|---|
| | | | In Use | Not Running | Building | | | | |
| 3 Kjellin.... | 3 | Poldihütte Kladno, Austria. | 4.00 | ..... | ..... | Single phase alternating | 400 | Liq'd open hrth. steel. | Special quality steels. |
| 4 Kjellin.... | 4 | L. Brauns Söhne, Völklabrück, Austria. | 0.4 | ..... | ..... | Single phase alternating | 65 | Cold charge. | Special quality steels. |
| 5 Kjellin.... | 5 | Vickers Sons & Maxim, Sheffield, England. | ..... | 1.5 | ..... | Single phase alternating | 230 | Cold charge. | Special quality steels. |
| 6 Kjellin.... | 6 | Vickers Sons & Maxim, Sheffield, England. | ..... | 0.18 | ..... | Single phase alternating | 100 | Cold charge. | Special quality steels. |
| 7 Kjellin.... | 7 | Wm. Jessop & Sons, Sheffield, England. | 1.8 | ..... | ..... | Single phase alternating | 250 | Cold charge. | Special quality steels. |
| 8 Kjellin.... | 8 | Alti Forni Gregorini, Lovere, Italy. | 1.8 | ..... | ..... | Single phase alternating | 330 | Cold charge and liquid O. H. steel. | Tool steels, war material. |
| 9 Kjellin.... | 9 | Vidua de Urigoitia e Hija, Araya, Spain. | 1.5 | ..... | ..... | Single phase alternating | 215 | Cold charge. | Special quality steels. |
| 10 Kjellin.... | 10 | Eisenwerk Domnarfvet, Gysinge, Sweden. | 1.50 | ..... | ..... | Single phase alternating | 175 | Cold charge. | Special quality steels. |
| 11 Kjellin.... | 11 | Sybry Searles Ltd., Trollhättan, Sweden. | 2.00 | ..... | ..... | Single phase alternating | 300 | Cold charge. | Special quality steels. |
| 12 Kjellin.... | 12 | General Electric Co., Pittsfield, Mass., U. S. | .40 | ..... | ..... | Single phase alternating | 100 | ..... | Test furnace. |

## (b) INDUCTION FURNACES (*Continued*)

| Type | No. | Firm | With Metric Tons Charge | | | Current | Kw. Used | Kind of Charge | Use of Product |
|---|---|---|---|---|---|---|---|---|---|
| | | | In Use | Not Running | Building | | | | |
| 13 Kjellin.... | 13 | General Electric Co., Schenectady, N. Y., U. S. A. | .1 | ..... | ..... | Single phase alternating | 50 | ..... | Test furnace. |
| 14 Kjellin.... | 14 | Deere & Co., Moline, Illinois, U. S. A. | ..... | ..... | .75 | Single phase | 150 | Cold charge. | Steel castings. |
| 15 Kjellin.... | 15 | Carnegie Technical Institute, Pittsburg, Pa., U. S. A. | .10 | ..... | ..... | Single phase | 30 | Cold charge. | Test furnace. |
| 16 Röchling-Rodenhauser | 1 | Röchlingsche Eisen & Stahlwerke, Völklingen, Germany. | 8. to 10. | ..... | ..... | Single phase | 750 | Liquid basic Bessemer steel. | Special quality steel, rails, etc. |
| 17 Röchling-Rodenhauser | 2 | Röchlingsche, Eisen & Stahlwerke, Völklingen, Germany. | 2.0 | ..... | ..... | Three phase alternating | 275 | Liquid basic Bessemer steel. | Special quality steel, rails, etc. |
| 18 Röchling-Rodenhauser | 3 | Röchlingsche, Eisen & Stahlwerke, Völklingen, Germany. | 2.0 | ..... | ..... | Three phase alternating | 275 | Liquid basic Bessemer steel. | Special quality steel, rails, etc. |
| 19 Röchling-Rodenhauser | 4 | Röchlingsche, Eisen & Stahlwerke, Völklingen, Germany. | 2.0 | ..... | ..... | Three phase alternating | 275 | Liquid basic Bessemer steel. | Special quality steel, rails, etc. |
| 20 Röchling-Rodenhauser | 5 | Eberle & Co., Augsburg, Germany. | ..... | ..... | 2.0 | Single phase alternating | 275 | Cold charge. | Steel castings. |

| Type | No. | Firm | With Metric Tons Charge | | | Current | Kw. Used | Kind of Charge | Use of Product |
|---|---|---|---|---|---|---|---|---|---|
| | | | In Use | Not Running | Building | | | | |
| 21 Röchling-Rodenhauser | 6 | Bergische Stahlindustrie, Remscheid, Germany. | 5.0 | ..... | ..... | Single phase alternating | 500 | Liquid O.H. steel. | Special quality steel. |
| 22 Röchling-Rodenhauser | 7 | Le Gallais Metz & Co., Dommeldingen, Luxemburg. | 3.5 | ..... | ..... | Single phase alternating | 380 | Liquid pig iron from mixer. | Special quality steel castings and low carbon steel. |
| 23 Röchling-Rodenhauser | 8 | Le Gallais Metz & Co., Dommeldingen, Luxemburg. | 3.5 | ..... | ..... | Single phase alternating | 380 | Liquid pig iron from mixer. | Special quality steel castings and low carbon steel. |
| 24 Röchling-Rodenhauser | 9 | Le Gallais Metz & Co., Dommeldingen, Luxemburg. | .75 | ..... | ..... | Single phase alternating | 100 | Liquid pig iron from mixer. | Special quality steel castings and low carbon steel. |
| 25 Röchling-Rodenhauser | 10 | Le Gallais Metz & Co., Dommeldingen, Luxemburg. | 1.5 | ..... | .... .. | Three phase alternating | 275 | Liquid pig iron from mixer. | Special quality steel castings and low carbon steel. |
| 26 Röchling-Rodenhauser | 11 | Le Gallais Metz & Co., Dommeldingen, Luxemburg. | 3.5 | ..... | ..... | Single phase alternating | 380 | Liquid pig iron from mixer. | Special quality steel castings and low carbon steel. |

## (b) INDUCTION FURNACES (*Continued*)

| Type | No. | Firm | With Metric Tons Charge | | | Current | Kw. Used | Kind of Charge | Use of Product |
|---|---|---|---|---|---|---|---|---|---|
| | | | In Use | Not Running | Building | | | | |
| 27 Röchling-Rodenhauser | 12 | Acieries de la Marine et d' Home court, St. Chamond, France. | 3. | ..... | ..... | Three phase alternating | 350 | Liquid or cold charge. | Special quality steel. |
| 28 Röchling-Rodenhauser | 13 | Acieries Léigeoises, Bressoux-les-Liége, Belgium. | ..... | 1.0 | ..... | Three phase alternating | 200 | Cold charge. | Castings. |
| 29 Röchling-Rodenhauser | 14 | Kronwerke Slatoust, Russia. | 1.00 | ..... | ..... | Three phase alternating | 175 | Cold charge. | War material. |
| 30 Röchling-Rodenhauser | 15 | Ricardo, Honey, Mex. | 2.5 | ..... | ..... | Three phase alternating | 300 | Liquid pig iron and ore. | Special quality steel. |
| 31 Röchling-Rodenhauser | 16 | Crucible Steel Casting Co., Lansdowne, Pa., U. S. A. | ..... | ..... | 2.0 | Single phase | 300 | Cold charge. | Castings. |
| 32 Röchling-Rodenhauser | 17 | Stavanger Electro-Staalverk Co., Stavanger, Norway. | ..... | ..... | 3.5 to 4.0 | Single phase | 340 to 450 | Liquid charge. | High grade tool steel, castings. |
| 33 Röchling-Rodenhauser | 18 | Peiner Walzwerk, Peine, Germany. | ..... | ..... | 3.5 to 4.0 | Two phase | 450 to 500 | Cold ferromanganese. | Molten ferromanganese for converters. |
| 34 Röchling-Rodenhauser | 19 | Imperial Japanese Steel Works, Wakamatsu, Japan. | ..... | ..... | 5. | Two phase | 550 | ? | ? |

## (b) INDUCTION FURNACES (*Continued*)

| Type | No. | Firm | With Metric Tons Charge | | | Current | Kw. Used | Kind of Charge | Use of Product |
|---|---|---|---|---|---|---|---|---|---|
| | | | In Use | Not Running | Building | | | | |
| 35 Röchling-Rodenhauser | 20 | Gelsenkirchner Bergwerks Verein Abt, Rothe Erde, Aachen, Germany. | ..... | ..... | 3.5 to 4 | Two phase | 450 to 500 | Cold ferromanganese. | Molten ferromanganese for converters. |
| 36 Frick..... | 1 | Friedr. Krupp A. G., Essen, Germany. | 10 | ..... | ..... | Single phase | 750 | ..... | High grade steel. |
| Schneider.... | 1 | Schneider & Co., Creusot, France. | 1.0 | ..... | ..... | ..... | ..... | ..... | Test furnace. |
| Hiorth..... | 1 | Norway..... | 5.0 | ..... | ..... | Single phase | 500 | Cold charge. | High grade billets. |
| Special Type.. | 1 | Forges de St. Jacques, Montluçon, Fr. | ? | ..... | ..... | ..... | ..... | ..... | ..... |

## (c) COMBINED ARC AND RESISTANCE FURNACES

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Nathusius.... | 1 | Oberschlesisches Eisenbahn- Bedarfs- Akt-Ges. Friedenshütte. | 5.0 | ..... | ..... | Three phase alternating | 750 | Liquid steel from converter or O. H. | Soft and hard special quality steels. |
| Nathusius.... | 2 | Oberschlesisches Eisenbahn- Bedarfs- Akt-Ges. Friedenshütte. | 1.0 | ..... | ..... | Three phase alternating | 250 | Liquid steel from converter or O. H. or cold charge. | Test charges. |

# *Part Two*

## A. THE MATERIALS USED IN FURNACE CONSTRUCTION, AND THE COSTS OF OPERATION

### THE MATERIALS USED IN FURNACE CONSTRUCTION

By Dipl. Ing. W. Rodenhauser, E.E.

It has already been pointed out several times that a great advantage of the electric furnace over other metallurgical furnaces is that it enables the generation of desirable high temperatures. Generally speaking this possibility is made use of, and work is carried out at higher temperatures than in gas fired furnaces. On this account, therefore, it is immediately apparent that the materials used for furnace construction, especially those parts in contact with the highly heated charge, have to meet particularly high requirements. Mistakes in the choice of these materials can very quickly bring about trouble in the working of the furnace and, under certain conditions, can completely stop the operation.

During the discussion of the different furnaces the materials at present used for their construction were mentioned, but it still appears advantageous in the following pages to treat these materials as a whole, and with special regard to the conditions of service.

The first requirement to be demanded is *resistance to the high temperatures reached in the furnace.* This needs, in the first place, a high melting point, which is usually measured by means of Seger cones. These are named after their inventor Seger. They are small three-cornered pyramids made of various mixtures of silicates, and are about 2.36″ high. The softening

point, with increasing temperatures, is carefully observed. The following table gives the comparison between degrees Centigrade and Seger cone numbers.

| No. | Temp. | No. | Temp. | No. | Temp. | No. | Temp. |
|---|---|---|---|---|---|---|---|
| 022 | 600 | 07a | 960 | 9 | 1,280 | 29 | 1,650 |
| 021 | 650 | 06a | 980 | 10 | 1,300 | 30 | 1,670 |
| 020 | 670 | 05a | 1,000 | 11 | 1,320 | 31 | 1,690 |
| 019 | 690 | 04a | 1,020 | 12 | 1,350 | 32 | 1,710 |
| 018 | 710 | 03a | 1,040 | 13 | 1,380 | 33 | 1,730 |
| 017 | 730 | 02a | 1,060 | 14 | 1,410 | 34 | 1,750 |
| 016 | 750 | 01a | 1,080 | 15 | 1,435 | 35 | 1,770 |
| 015a | 790 | 1a | 1,100 | 16 | 1,460 | 36 | 1,790 |
| 014a | 815 | 2a | 1,120 | 17 | 1,480 | 37 | 1,825 |
| 013a | 835 | 3a | 1,140 | 18 | 1,500 | 38 | 1,850 |
| 012a | 855 | 4a | 1,160 | 19 | 1,520 | 39 | 1,880 |
| 011a | 880 | 5a | 1,180 | 20 | 1,530 | 40 | 1,920 |
| 010a | 900 | 6a | 1,200 | 26 | 1,580 | 41 | 1,960 |
| 09a | 920 | 7 | 1,230 | 27 | 1,610 | 42 | 2,000 |
| 08a | 940 | 8 | 1,250 | 28 | 1,630 | | |

A material is called refractory if its softening point lies about No. 26, and very refractory if the latter is between 30 and 36.

Without going further into the properties which influence the refractoriness of the furnace materials, we will learn the requirements they have to meet.

The first consideration is that in electric furnaces the materials are exposed not only to high temperatures, but also to chemical influences. Naturally the results of these influences must be felt as little as possible. We can give as the second requirement *great resistance to chemical influences*. Unfortunately these harmful influences cannot be altogether prevented, and it is necessary to reduce them as much as possible. This is partially brought about by having the greatest possible density and mechanical solidity of the materials. It is immediately evident that these properties are of important influence on the durability of the furnace masonry and lining, when it is realized that porous material offers much more surface for attack by harmful chemical influences than one that is dense. Further great density is

synonymous with good mechanical strength, so that a dense material will most successfully withstand the mechanical influences due to movements of the electric furnace.

The appearance of cracks in the furnace walls lead to the same bad results as the use of porous material, for they allow the harmful chemical influences to penetrate very deep, and offer a large surface for attack. This, therefore, brings about the requirements of the *ability to withstand the influence of changes of temperature.* These cracks are due to variations in the temperature, which bring about expansion and contraction in the materials used.

The requirements for the materials for furnace construction are therefore:

1. Ability to stand high temperatures.
2. Resistance against chemical influences.
3. Great density and mechanical strength.
4. Permanence of form under changes of temperature.

The materials to be considered are as follows, each of which will be taken up separately in the light of the above requirements:

1. "Schamotte" fire-bricks.
2. Acid or silica bricks.
3. Half "Schamotte" or half silica bricks.
4. Carbon bricks and carbon mixtures for ramming into place.
5. Basic bricks and basic material for ramming into place.
6. Mortar.

"Schamotte" fire-bricks are made from burnt fire-clay known as Schamotte or Chamotte, to which unburnt clay is added as a binding material. The clay shrinks more or less during the burning. The Schamotte must therefore be burnt as thoroughly as possible. The more Schamotte in proportion to clay is used in the brick mixture, the less is a strong shrinkage to be feared. Moreover, the shrinkage can be partially neutralized by adding quartz or quartzite which expand during heating to the mixture.

Under all conditions the shrinkage of the "Schamotte" brick is to be most carefully kept in mind, because, for example, the use of this material in furnace roofs would be disastrous.

As opposed to the "Dinas" silica bricks, which will shortly be described, these fire-bricks have the advantage that they are not so sensitive to changes of temperature, and this advantage is more marked the less unburnt clay is used in the mixture.

Their chief importance in electric furnace work is for heat insulation purposes, and they are used in this way, for example, in the induction furnaces. For furnace roofs they are only applicable if the temperature attained is not very high, and therefore at the most can be used only for induction furnaces.

Acid or silica bricks are greatly used in electric furnaces for roofs. They are very rich in silica, and are made from quartzite with 95 to 99% silica, and ought to have at least 95% when finished. They are known to the trade as English "Dinas" or Lime Dinas bricks. For the Lime Dinas bricks an addition of 1 to 2% of limes is used as a binding agent, usually in the form of cream of lime. If clay is used instead of lime the quality is not quite so good, the bricks containing 80 to 90% silica, and being known as Clay Dinas or German Dinas bricks.

As has been mentioned, these bricks expand considerably with increasing temperature. This is less noticeable in bricks made from certain quartzites, but is unavoidable even with the best materials. Their greatest use is for the roofs of furnaces with high roof temperatures, such as all the arc furnaces have, and because of their expansion with heat a very flat roof can be maintained. Unfortunately these bricks are very sensitive to changes of temperature, and offer only small resistance to the action of slags. They are therefore practically restricted to roof construction.

The half Schamotte or half silica bricks are between the two kinds of brick just described. They consist of a mixture of quartz and burnt clay, and have properties corresponding to an excess of one or the other constituent.

Carbon bricks and carbon mixtures for ramming into place are not used in steel-refining furnaces; because of the great affinity between iron and carbon they are quickly destroyed, and undesirable carbon enters the metal. On the other hand carbon mixtures have been often used in electric shaft furnace

experiments in their double capacity as refractory materials and conductors of the current. Apart from this, carbon bricks or mixtures are not used for electric furnace construction.

Basic bricks and materials, however, are so important that they are used almost exclusively for the hearths and walls of electric steel-making furnaces. They include chrome iron ore, or chromite, dolomite, and magnesite.

Of these materials chromite is not used in Germany. It has the disadvantage that if it comes in direct contact with the metal it is rapidly destroyed, and influences the bath in an unwished-for and harmful way.

Dolomite is finding increasingly large application. It is a limestone with a large percentage of magnesia, $CaCO_3$ $MgCO_3$, and is found in large amounts in Thüringen and Lothringen, and in various parts of the United States. Its greatest use in the iron and steel industry is as a lining for the basic Bessemer converter for which it is prepared in so-called dolomite plants. The method of preparation may be briefly described:

The raw dolomite is either broken by hand, or crushed, to pieces about the size of one's fist. These pieces are then burnt in a shaft furnace to a clinker. The amount of coke necessary is from 20% to 30% of that of the raw stone. After burning, the clinker is ground in a suitable mill, the largest pieces being not more than 0.4″ diameter. The ground dolomite is then mixed with about 7 to 10% of hot dry tar, on a moderately heated floor. This mixing is carried out either by hand or in a chili mill, or suitable mixing machine, which is so constructed that the material can be heated. Careful attention must be paid to the preparation of the tar if the basic dolomite-tar mixture is to have the best properties. The crude tar is distilled in special apparatus at 240–280° C., and is freed in this way from the ammonia water and light oils. It must be mentioned that the burnt dolomite, because of its large lime contents, readily absorbs moisture from the air and falls to powder. It should, therefore, be used as soon after its preparation as possible, and is applicable to the making of bricks, or for ramming into place.

Magnesite, as well as dolomite, is finding an increasingly

large use for those parts of the furnace in direct contact with the charge, and indeed for all those parts exposed to specially high temperatures. It has an advantage over dolomite in that it is more neutral in character. When mined it has a melting point about equal to Seger cone, No. 42. As it shrinks a great deal when heated, it must, before using, be burnt so thoroughly that it is sintered. For this a temperature of about 1700° C. is necessary, and the Sp. Gr. rises from 3.19 to 3.65. If the magnesite is to be used direct, it is mixed with tar, like the dolomite, and rammed into place. If, however, it is to be made into bricks, no tar is used. The finely powdered magnesite is forced into shape by the use of very high hydraulic pressure, and then again burnt.

Apart from its greater neutrality magnesite has the further advantage over dolomite that it is not so sensitive to the action of moisture, and when burnt to sinter can be kept in storage without fear of spoiling. On account of its great density, however, it easily cracks when subjected to changes of temperature, but does not shrink very much with increasing temperature, and because of this is being used more often for furnace roofs.

When building electric furnaces a suitable mortar must be used. Here again permanence of form under changes of temperature is of the first importance, and the mortar must be carefully considered in this respect. Also the courses should be laid as close as possible, so that even with expansion of the mortar the joints may remain tight, and expose very small surfaces of attack to harmful influences. As a general rule it may be said that the mortar should be of the same nature as the rest of the construction, *using basic mortar with basic materials, and acid with acid.* Thus with dolomite bricks either tar alone is used, or tar mixed with dolomite as a binding material, while with magnesite bricks powdered magnesite is used mixed either with tar or a little hydrochloric acid. With other than basic brickwork a certain amount of quartz or white silica sand is usually mixed with the mortar, an excess of clay being avoided, and care again being taken to have tight joints.

Reconsidering the materials of construction we see that none of them possesses completely the qualities that have been men-

tioned, so that they must be carefully chosen and used with proper regard to their properties. This leads us to a point that must not be left without attention. It is that, under the influence of other materials at high temperatures, certain refractories quickly break down. The following rule must be strictly observed: *In the presence of basic influences use basic materials, and with acid influences use acid materials.* Therefore, in a furnace in which the basic process is to be carried out, basic materials must be used completely or at least in those parts where the temperature is high enough for one material to act on the other. For instance not alone the hearth and walls but the cupola-like roof of the Stassano furnace is built of basic material, the roof being of magnesite bricks, and the hearth of either dolomite or magnesite bricks, or these materials mixed with tar and rammed into place. On the other hand, in the Héroult and Girod furnaces the hearth is basic but the roof is of silica bricks. This is only possible when no danger of fusion is to be feared at the junction of the two materials. It should be remembered that quartz and clay, or mixtures of the two, so greatly lower the melting points of dolomite or magnesite as to bring them from Seger cone 17 to 11, which would naturally lead to the rapid destruction of any electric furnace if it took place.

The extremely harmful occurrences mentioned here must be prevented, either by the use of basic material exclusively, or else the contact between the acid roof and basic hearth must be removed from the influence of harmful temperatures.

It may be mentioned here that the lowering of the fusion point of a refractory material is often brought about purposely, however only to a certain degree. For instance, in making a hearth of magnesite, slag, clay, or similar material is often added as a flux, to bring about a more ready sintering of the mass. In this way the hearth is made denser, and offers greater resistance to the influence of the metal and slags. Naturally only the smallest amount of flux necessary must be used in order not to reduce the melting point too much.

In the design of electric furnaces the properties of the ma-

terials to be employed should be carefully kept in mind. In the first place the hearth ought to be of such a shape that, after a charge or a short run, repairing can be carried out. This is necessary because of the unavoidable action of the slag on the lining. This is completely possible at present only in that furnace which is patterned after the open hearth, namely, the Héroult. All other furnaces allow a certain amount of relining, but because of the vertical or almost vertical walls it is impossible to keep the hearth longer than about three weeks. After this time a new one is necessary, equally with the Stassano, Girod, or Röchling-Rodenhauser. Notwithstanding this, the previous discussions on costs of operation have shown that the lining costs of the Héroult and Röchling-Rodenhauser are about the same. This is because of the more rapid destruction of the roof in the arc, as opposed to the induction furnace.

It is because of these considerations that the Stassano and Girod furnaces do not have such good lining costs as the Héroult and Röchling-Rodenhauser. In case bricks are not used the new hearth is made up of hot magnesite or dolomite mixture rammed into place. If this work has been carried out by hand it can be more profitably done by means of compressed-air hammers which are sold by all the firms making compressed-air tools. Air at a pressure of about six atmospheres is used. These tools bring about a great saving in labor, and have the advantage that they also give a much denser and more solid hearth than hand ramming. Naturally if such a lining is heated, which corresponds somewhat to the burning of refractory bricks, an expansion takes place. This will certainly give rise to cracks unless a certain freedom of movement is allowed for. This is well provided for by leaving a space between the hearth and the insulating cover, which may be filled with loose granulated material.

In all arc furnaces the roof should be made removable, for repairs are not possible during the operation. In this way a new roof can easily and quickly be put into place. As the bricks used for the roofs are sensitive to changes of temperature, it is evident that there will be more danger, the more water-cooled openings there are through which to pass electrodes. In

regard to further details concerning the construction of the various types of electric furnaces, reference must be made to the chapters of the earlier part of the book, in which the furnaces are separately considered.

## THE COSTS OF OPERATION

The question of the operating costs of electric-steel and pig-iron processes is undoubtedly the most important one after that of the quality of the product. These two questions therefore will determine which types of furnace will advance in the future, and which will recede. With regard to the quality it is generally acknowledged that all the accepted types of electric furnaces, those considered in detail in the chapters of the first part of the book, will produce steel that will answer all requirements. However, the possibility is often mentioned of an unfavorable influence on the quality of the steel of the unnecessarily high temperatures of the arc furnaces. This possibility is brought up again and again, and was recently spoken of by Henry M. Howe, Professor of Metallurgy in Columbia University (*E. & M. J.*, Aug., 1909).

The certainty of different methods of heating causing a difference in quality can only be proved if two steels are made of the same composition, one in an arc and the other in an induction furnace, the same charge to be used in each case, and equal expert supervision given; then the two steels to be thoroughly tested to see whether they give different results. Unfortunately, such a test has not yet been made.

Until this is done, we must admit that steel made in the different furnaces, with expert supervision of the metallurgical processes, has the same excellent properties. There remains, therefore, only the question of the operating costs to determine which type of furnace to adopt and the economy of electric steel production. Calculations of the operating costs of the different types of furnaces have been published many times, so that it would appear very simple to compare them one with the other. This would immediately show which one would allow the cheapest

production of steel, and the difficult question of the choice of the most suitable and economical type of furnace would be solved at one blow. Unfortunately this method is altogether incapable of giving a view corresponding to the real conditions. The figures that one usually finds published are often misleading. However, some of them should be considered later, for with proper care they will give much interesting information.

First we will see which factors are of importance in influencing the operating costs.

They are briefly:

1. The materials charged.
2. The loss during the operation.
3. The consumption and price of the current.
4. The fluxes.
5. The labor costs.
6. The costs of linings and repairs.
7. Amortization.
8. Costs of electrodes.
9. Auxiliary appliances.
10. Tools.

In regard first of all to the material charged, it can be of metal below the average in quality, and therefore cheaper, for all electric furnaces which are suitable for refining. This is because these furnaces allow a very complete removal of all harmful impurities. The induction furnaces with ring-shaped hearths, such as the Kjellin furnace, do not allow thorough refining to be carried out, as has been pointed out in the previous chapters. For these furnaces, therefore, especially pure and correspondingly dearer raw materials must be chosen, similar to those now used in the crucible process. This includes the high-priced Swedish irons, as well as the purest refined metal, usually made from Styrian charcoal pig iron; also fluid metal already refined in the open-hearth furnace, which can be "killed" in the electric furnace, in exactly the same way as in the crucible. Such a furnace is therefore at a decided disadvantage with regard to the metal charged compared with other furnaces, notwithstanding that a considerably lower power consumption is naturally re-

quired for the further working up of pure raw material compared with material that must be first refined in an electric furnace of another construction.

For these electric refining furnaces, the cost of the charge can be taken as equally high when comparing the operating costs. When comparing the costs of the open-hearth and electric furnace it must not be left out of consideration that the latter has the advantage that it *allows the use of more impure and therefore cheaper raw materials, at the same time permitting the production of the highest quality steels.*

It appears unnecessary to give here any figures on the price of scrap, for as already mentioned this price is strongly dependent on local conditions. This also applies to fluid charges from either the blast furnace, cupola, open-hearth furnace, or converter.

### THE LOSS DURING THE OPERATION

This means the material lost during the treatment of the molten metal in the electric furnace. Compared with other furnaces it is very small. When using the purely induction furnace with ring-shaped hearth, in which the purest material must be used, the loss is not considered at all; it can be put down as zero. On the other hand, when carrying out refining in the electric furnace, a certain loss is unavoidable. Altogether apart from the slagging of the impurities, small amounts of the liquid metal are torn away when the slag is removed. This loss is therefore the greater the more impurities are present in the charge which necessitates a more frequent making and removal of slags. One will scarcely make a mistake in taking this loss, depending on the charge, as about the same in all electric refining furnaces. It should be figured on the average as 4 to 6 per cent. with a solid charge, and 2 to 3 per cent. with a liquid charge.*

In this connection it must be remembered that very light

*Borchers gives the loss as 10 to 11 per cent. in a Girod furnace with a cold charge.

thin scrap can be used in the electric furnace such as waste wire, turnings, etc., without the loss being higher than the figures given above. This is because the strongly oxidizing action of the hot gases of the open hearth is not present in the electric furnace. For comparison it may be mentioned that the loss in the open-hearth scrap process ordinarily amounts to 4 to 8 per cent., and is considerably higher if much of the light scrap, mentioned above, is used.

If a pig-iron process is carried out in the electric furnace, which can offer an economic advantage under very favorable prices for current, then more iron is reduced from the ore than is the case in the open hearth, so that the yield is easily greater in amount than that charged. In this respect the electric furnace works more cheaply than the open hearth, and further allows the production of a higher quality of steel than can be produced in the open hearth. This is shown very plainly in that steel is often taken from the open hearth to the electric furnace to be refined, or to be alloyed, etc.

In view of these advantages, why is not the electric furnace used more often for melting, in place of the open hearth? The answer is found immediately if we consider the cost of heating, on the one hand in the open-hearth or crucible furnace, on the other hand in the electric furnace. The fuel consumption in the open hearth, working the scrap process and using bituminous coal, amounts to 22% to 32% of the output. If we take the highest value, and remember that the electric furnace in the sizes used up to now can only be compared with small open-hearth furnaces, we find that 705.5 lbs. of coal would be used per metric ton of open-hearth steel. In the electric furnace 750 to 800 kw. hours would be necessary to melt the scrap used in the open hearth, *and* to refine it to the same grade as ordinary open-hearth steel, provided that the furnace was of 5 to 8 tons capacity. If the coal cost $3.57 per ton, then the heating cost alone of the open hearth would be $1.12 per metric ton. In order that the heating cost in the electric furnace should not exceed that of the open hearth, the kw. hour, with the above assumptions, should cost 0.15c.

If the kw. hour prices are calculated, which are allowable with different prices of coal and coal consumption, so that the heating costs in the electric furnace do not exceed those in the open hearth, then the following table is obtained:

| Coal Used per Metric Ton of Open-Hearth Steel | Allowable Price per Kw. Hr. in Cents with Coal at the Following Price per Metric Ton (2,204 Lbs.): | | | | | | | If there is Used per Metric Ton of Electric Steel |
|---|---|---|---|---|---|---|---|---|
| | $2.85 | $3.33 | $3.80 | $4.28 | $4.76 | $5.23 | $5.71 | |
| 22 | .0833 | .097 | .111 | .126 | .140 | .154 | .166c. | |
| 24 | .090 | .107 | .121 | .138 | .152 | .166 | .183 | |
| 26 | .100 | .116 | .130 | .147 | .164 | .180 | .197 | 750 |
| 28 | .107 | .123 | .140 | .159 | .178 | .195 | .214 | kw.hrs. |
| 30 | .114 | .133 | .152 | .171 | .190 | .209 | .228 | |
| 32 | .121 | .142 | .161 | .183 | .202 | .223 | .238 | |
| 22 | .078 | .090 | .104 | .116 | .130 | .142 | .157c. | |
| 24 | .085 | .100 | .114 | .128 | .142 | .157 | .171 | 800 |
| 26 | .092 | .107 | .123 | .138 | .154 | .169 | .185 | kw.hrs. |
| 28 | .100 | .116 | .133 | .150 | .166 | .183 | .200 | |
| 30 | .107 | .123 | .142 | .159 | .178 | .195 | .214 | |
| 32 | .114 | .133 | .152 | .171 | .190 | .209 | .228 | |
| 22 | .073 | .085 | .097 | .109 | .123 | .135 | .147c. | |
| 24 | .080 | .092 | .107 | .121 | .133 | .147 | .161 | 850 |
| 26 | .086 | .102 | .116 | .130 | .145 | .159 | .173 | kw.hrs. |
| 28 | .092 | .109 | .126 | .140 | .157 | .171 | .188 | |
| 30 | .100 | .116 | .133 | .150 | .166 | .183 | .202 | |
| 32 | .107 | .123 | .142 | .161 | .178 | .197 | .214 | |

This table clearly shows how very much cheaper the heating costs are in the open-hearth than in the electric furnace. With the most unfavorable coal consumption (32%), and very high cost of coal ($5.71 per metric ton), the kw. hour ought not to cost more than 0.238c. If we calculate the kw. year as containing 300 working days, then the kw. year ought not to cost more than $17.14, or the e.h.p. year must not cost more than $12.62. It is evident that these prices for power can only be reached with the most favorable conditions, for example through the use of water-power. It is therefore also clear that the electric furnace can only be used for the melting of scrap, and the pro-

duction of steel, similar in quality to ordinary open hearth, in such places where the cheapest natural power is ready for use, or else where small amounts of steel are to be made for which the open-hearth process is unsuitable. In all other cases it is almost always preferable to leave only the final work to the electric furnace. In this way at only a small increase in cost an improved quality is reached, compared with open hearth which is greatly in favor of the electric furnace.

It has been mentioned already that the electric furnace can replace the crucible. If we therefore now consider the heating costs of the electric furnace on the one hand (using this method of working), and the crucible on the other, we obtain the following: The fuel consumption with crucible melting in coke furnaces not using the waste gases amounts to about 150 to 200 per cent. of coke, and with the use of regenerative gas furnaces, 175 to 200 per cent. coal.

If we take it, first, that the same pure charge is to be used in the electric furnace as in the crucible, then the melting capacity alone of the electric furnace comes into consideration. For this the power consumption is 600 to 750 kw. hrs. per metric ton of finished steel depending on the size of the furnace used. For instance, the firm of Krupp has brought the power consumption down to 617 kw. hrs. per metric ton in their 8-ton, ring-shaped induction furnaces, of the Kjellin and Frick types. Also, calculating on the melting alone, the power consumption in an 8-ton Röchling-Rodenhauser furnace is only 580 kw. hrs. per ton.

Taking the figures given above as a basis, the table on the following page clearly shows how high the cost per kw. hr. may be, in order that electric heating may not be dearer than that in the crucible furnaces with the given unit prices for coal and coke.

The table shows how the unit price for power can increase very considerably before the heating cost in the electric furnace will exceed that of the ordinary crucible furnaces. We had assumed previously that only pure raw materials were used. In this way, however, only a part of the advantage of the electric furnace is utilized since the remarkable properties that it shows

as a refining furnace remain unemployed. We should obtain, therefore, a still more favorable idea of the electric furnace if we used less pure and, therefore, cheaper raw material in the charge. Although from 150 to 250 kw. hrs. more would be required, depending upon the degree of purification, this increase would scarcely outweigh the savings brought about by the use of a cheaper charge.

| Coal Used per Metric Ton of Crucible Steel Per cent. | Allowable Price per kw. hr. in Cents with the Following Coal or Coke Prices (per Metric Ton): | | | | | | | | If there is Used per Metric Ton of Electric Steel kw. hrs. |
|---|---|---|---|---|---|---|---|---|---|
| | $2.38 | $2.85 | $3.33 | $3.80 | $4.28 | $4.76 | $5.23 | $5.71 | |
| 150 | .595 | .714 | .833 | .952 | 1.071 | 1.190 | 1.309 | 1.428 | 600 |
| 175 | .695 | .833 | .971 | 1.111 | 1.250 | 1.388 | 1.528 | 1.666 | |
| 200 | .795 | .952 | 1.111 | 1.269 | 1.428 | 1.588 | 1.745 | 1.904 | |
| 150 | .547 | .659 | .769 | .881 | .988 | 1.100 | 1.209 | 1.319 | 650 |
| 175 | .643 | .769 | .897 | 1.028 | 1.115 | 1.281 | 1.409 | 1.540 | |
| 200 | .733 | .881 | 1.028 | 1.171 | 1.316 | 1.464 | 1.614 | 1.762 | |
| 150 | .512 | .612 | .714 | .816 | .919 | 1.021 | 1.123 | 1.224 | 700 |
| 175 | .595 | .714 | .833 | .952 | 1.071 | 1.190 | 1.309 | 1.428 | |
| 200 | .681 | .816 | .952 | 1.088 | 1.226 | 1.362 | 1.500 | 1.633 | |
| 150 | .476 | .571 | .666 | .762 | .857 | .952 | 1.047 | 1.143 | 750 |
| 175 | .557 | .666 | .778 | .890 | 1.000 | 1.112 | 1.221 | 1.333 | |
| 200 | .635 | .762 | .890 | 1.016 | 1.143 | 1.269 | 1.397 | 1.524 | |

It must be further considered that much more labor is required to operate the crucible furnaces than an electric furnace, which can replace many crucibles because of its capacity. This latter property brings about a further advantage, namely, a complete uniformity of the whole cast, while the material from different crucibles shows certain variations. It should also be mentioned that the cost of crucibles is higher than that of the upkeep of an electric furnace. Finally when one considers that the steel from the electric furnace is of fully equal value to that from the crucible, then the displacing of the crucible

by the electric furnace appears inevitable. This is shown by the growth that the electric-furnace industry has had even up to now. The following figures in metric tons are taken from the steel production of Austria-Hungary:

| Year | Crucible Steel | Electric Steel |
|---|---|---|
| 1907 | 23,215 | ..... |
| 1908 | 19,659 | 4,333 |
| 1909 | 16,083 | 9,048 |
| 1910 | 17,586 | 20,028 |
| 1911 | 17,467 | 22,867 |

We have previously shown that, in regard to heating costs, the electric furnace is more economical in almost all cases than the crucible furnace, but that on the other hand it usually is less economical that the open hearth. This naturally brings it about that as much as possible of the melting and refining should be done in the more cheaply operated open hearth; or, in the case of the refining of basic Bessemer metal, in the converter. This leaves only refining and desulphurization for the electric furnace, for both of which purposes it is particularly suitable, because of the easy regulation of the temperature, and the removal of the harmful influences which are unavoidable with any other method of heating.

It is, therefore, to be expected that the electric furnace will not only displace crucible plants, but will be introduced more and more in connection with open-hearth and Bessemer plants.

The power consumption necessary for the work of refining naturally depends greatly on the final product desired, but it is also dependent upon the degree of purity the material has, when charged into the electric furnace. Furthermore, the size of the furnace, as well as the efficiency of the particular type of furnace chosen, has an influence which must not be neglected. In regard to these latter influences, the discussion in the first part of the book must be consulted.

The only points remaining to be considered are those of the material charged, and the final product required.

It is known that in melting in any furnace a higher efficiency is obtained the quicker the melting proceeds, that is, the greater the amount of energy supplied, the higher the efficiency. With an important lessening of the time necessary for melting, there is a corresponding lowering in the amount of heat lost by radiation, etc. It is also well known that, after the melting stage is once over, the following refining period cannot be lowered at will by increasing the amount of energy introduced, but that this refining work requires a certain time. As already mentioned several times, the slag must be changed more frequently depending on the impurity of the charge and the required purity of the final steel. The curve given in Fig. 60 (see Part I, page 134), which shows the power consumption depending upon the size of the furnace with different slag changes, gives a fitting idea of the influence of the impurities in the charge on the power consumption. The figures given should therefore be considered as approximate. To give more exact values is apparently only possible with a thoroughly fixed type of furnace, of a fixed size, and with an exactly established charge and final material.

For example, basic Bessemer metal with about 0.08% P and 0.08% S, requires an average of 250 kw. hrs. per metric ton for refining, in an 8-ton Röchling-Rodenhauser furnace, when the final material required is of crucible steel quality with a definite carbon content. With the production of the highest value alloy steels the power consumption under almost the same conditions increases to 280 and even 300 kw. hrs. per metric ton. On the other hand, when making structural steels it falls to 200 kw. hrs. or less. The power consumption is therefore the smallest when only a limited alloying or degasification must be carried out, and not a thorough refining of the metal. It then falls even to 100 kw. hrs. and less per ton.

It should be remembered that very impure metal was taken for the charge, basic Bessemer, and if metal was taken from the open hearth for example, with 0.03% P and 0.05% S, then under the same conditions there would be a certain lowering of at least 50 kw. hrs. per metric ton when making high quality steels.

The considerations given above serve to show that the power consumption figures given in technical papers should be carefully investigated to see what conditions they refer to, for such figures only lead to grave mistakes in many cases.

As the electric pig-iron furnace is beginning to be of importance, as shown by the action of the Jernkontoret in Sweden, who have built a furnace for a daily output of 20 tons with an energy consumption of 2500 to 3000 h.p., a comparison is given below between the ordinary blast and electric shaft furnace. The following table, due to *Catani*, is taken from *Neumann's* paper in *Stahl und Eisen*, 1909, p. 276, *ff*. It shows what unit prices may be paid for electrical power so that the heating cost in the electric furnace does not exceed that of the ordinary furnace, with the given price of coke and output per h.p. day:

| Weight of Pig Iron in 24 Hours per H.P. | | Allowable Price per H.P. Year with the Following Coke Prices: | | |
|---|---|---|---|---|
| kg. | lb. | $3.80 | $5.71 | $7.61 |
| 6 | 13.2 | $4.88 | $7.31 | $9.76 |
| 8 | 17.6 | 6.09 | 9.14 | 12.19 |
| 10 | 22.0 | 7.61 | 11.42 | 15.23 |
| 12 | 26.4 | 8.57 | 12.85 | 17.14 |

By calculation we obtain the following table, taking the h.p. year as equalling 0.736 kw. year, and the year as containing 365 days:

| Weight of Pig Iron in 24 Hours per Kw. | | Allowable Price per Kw. hr. in Cents with the Following Coke Prices: | | |
|---|---|---|---|---|
| kg. | lb. | $3.80 | $5.71 | $7.61 |
| 8.15 | 18 | 0.073c. | 0.109c. | 0.145c |
| 10.9 | 24 | .090 | .135 | .183 |
| 13.6 | 30 | .114 | .171 | .226 |
| 16.3 | 36 | .128 | .192 | .257 |

In order to be able to form an opinion from the figures given in the table, it is naturally necessary to know what efficiency is

possible today with the electric pig-iron furnace, per kw. day. This naturally depends in the first place on the quality of the ore used. In the following chapters the metallurgical part of this work will be gone into, but the table already shows that with coke at a relatively high price, the price for electricity must be very low for the electric-shaft or pig-iron furnace to compete with the ordinary one. In Germany, therefore, the electric-shaft furnace apparently has no future. This is clearly shown in the following table by Neumann (*Stahl und Eisen*, 1904, p. 143). Here the carbon necessary for the reduction of the various ores used in Germany, and that replaceable by electric power is calculated and given in money value. The price of coke is taken as $3.57 per metric ton, and that of power as 0.238c. per kw. hr., or $19.04 per h.p. year.

| Iron Ore | Pig Iron | Carbon | | The Carbon Replaceable by Electrical Energy | | | | Increased Cost of Electrical Heating |
|---|---|---|---|---|---|---|---|---|
| | | | | Corresponds | | Costs | | |
| | | Necessary for Reduction | Replaceable by Kw. hr. | Coke | Kw. Hr. | Coke | Kw. Hrs. | |
| Bilbas brown iron ore | Bessemer iron | 722.9 lb.<br>327.9 kg. | 1197.1 lb.<br>543. kg. | 1400.5 lb.<br>635.3 kg. | $2,579 | $2.269 | $7.881 | $5.590 |
| Dillenburger red iron ore | Foundry iron | 910.5 lb.<br>413.0 kg. | 1247.8 lb.<br>566. kg. | 1460.0 lb.<br>662.3 kg. | $2,688 | $2.364 | $8.190 | $5.826 |
| Luxemburg Lothringen Minette | Basic Bessemer | 509.3 lb.<br>231.0 kg. | 1261.0 lb.<br>572. kg. | 1475.7 lb.<br>669.2 kg. | $2,717 | $2.390 | $8.281 | $5.890 |
| Swedish Magnetite | Basic Bessemer | 1067.0 lb.<br>484.0 kg. | 806.9 lb.<br>336. kg. | 944.1 lb.<br>428.2 kg. | $1,636 | $1.528 | $4.985 | $3.457 |

The next question is: What unit prices for electrical power are obtainable today? This has been treated already in Chapter XV of the first part of the book, and it is therefore sufficient to give here merely the figures on which rough calculations can be based with the use of water-power 0.119c. and more per kw. hr. and more.

With the use of blast-furnace gas-engines..... 0.357c. to 0.714c.
Steam turbines of great efficiency.....0.714c. and more
Steam-engines.....0.952c. " "
Overland and large city central stations.....0.952c. " "

These figures show the values reached under the most favorable conditions. Apart from these, the prices naturally depend

very largely on local conditions, so that for more exact calculations these conditions must be considered. Further, the figures refer to the delivery of power at the generators, so that for exact calculations, the transmission losses, and losses in stationary or rotating transformers must also be considered. In the latter case, for example, these can easily amount to 20%, so that the cost of power at the furnace is 20% higher than at the central station.

We have now sufficiently considered the influence of current consumption and cost on the operating costs, and can pass on to the other points.

The *fluxes* necessary for the operation of electric furnaces depend in the first place on the amount of the impurities in the charge, and further on the desired composition of the final material. Also, on the method of carrying out the refining process, or on the furnace construction or method of heating, which under certain conditions may bring about a special method of working. As has been pointed out in previous chapters, lime and roll scale or ore are necessary during the oxidation stage. During the deoxidation stage, more lime, together with some sand or fluor-spar, are used to make it liquid, and some powdered carbon or ferro-silicon as special deoxidation medium. Carbon is used only in the Héroult furnace, all other arc furnaces and also the Röchling-Rodenhauser using ferro-silicon, so that in these latter furnaces a somewhat higher ferro-silicon consumption has to be figured upon than in the Héroult furnace. Further, all furnaces working with carbon electrodes use a slightly greater amount of oxidizing agents during the oxidation period compared with induction furnaces, due to the reducing action of the carbon vapor. This must be reckoned with, altogether apart from an increased power consumption.*

*The wages or labor costs* which are required for the operating of electric furnaces, calculated per ton of steel, are the smaller

* That an increased power consumption is required for arc furnaces compared with induction furnaces, due not only to the reducing atmosphere in arc furnaces but also because of the greater electrical loss, was proved in the first part of the book.

the greater the capacity of the furnace and the larger the amount of steel produced. In almost all cases the labor necessary to operate a small furnace will be completely satisfactory to operate a larger one. If we consider that the size of the various types of furnaces is the same, then the labor necessary for the purely metallurgical work can be taken as equal in amount. It should be determined whether solid or liquid charges are to be worked, and in the latter case the kind and amount of scrap to be charged, as well as the kind of auxiliary machinery to be used. If we also suppose that the number of men necessary to handle molds and work on ladles is the same under all conditions, for the different furnaces, (which appears to be absolutely correct,) then the same amount of labor would be used with all the furnaces for the purely metallurgical work.

We have already noticed, however, in the first part of the book that with the Stassano furnace one man is necessary to watch continuously the electrical recording instruments, and to regulate the electrodes according to their readings. Such a man is necessary with all arc furnaces unless they are provided with automatic regulating arrangements, and even if these are present a continuous supervision of the electrical conditions is necessary while the scrap is being melted, for example in the Héroult furnace, as has been already pointed out in Chapter VIII. This extra man is unnecessary with induction furnaces, and with proper design of the furnace all the switches and regulation devices can be looked after by the first melter without any great or important waste of time.

When working with fluid charges in arc furnaces equipped with automatic regulation no important switching work is necessary, and the special expense can be saved. These conditions are not without bearing on the amount paid for labor per ton of steel.

*The lining and repair costs* form a very important part of all operating costs. They include labor and the expense of material. The material costs, in the first place, depend largely on local conditions so that correct unit prices cannot be given. Apart from this the wear and tear on the furnace roof and walls

depend very largely on the method of heating. For this reason we find, for example, that the roof is strongly attacked in all arc furnaces, as it is exposed to the heat radiated from the arc, while an attack on the roof of induction furnaces can scarcely be noticed. The reason is that in the latter case the heat is produced in the metal bath itself so that the roof is protected by the covering of slag, altogether apart from the fact that at no place is a temperature of 3500° C. produced, as is sometimes the case near the carbon electrodes.

In all electric furnaces there is also a certain wearing away of the dolomite or magnesite hearth by the slag. As long as possible this is taken care of by repairs made between the charges. This is done the more easily if all parts of the hearth can be reached from the doors, and if the material used sticks to the places to be repaired. The Héroult furnace has the best shape, while the more cylindrical Girod and Stassano furnaces, as well as the Röchling-Rodenhauser only allow such repairs to a certain extent, so that after a run of a certain number of charges the furnaces must be stopped for repairing the walls, and in the case of the Girod and Grönwall, the bottom also. This brings about a certain loss of time and expense for labor, both of which are the greater depending on the difficulty of making the walls and roofs. The Stassano shows the most unfavorable conditions in this respect, while the Girod and Röchling-Rodenhauser can be prepared for operation in about the same time. With the latter a new lining is necessary after each 100 to 120 heats.

In regard to furnace repair costs it is evident that with arc furnaces the price of material for the roof as well as the hearth is of determining influence, while for induction furnaces the latter alone is of special importance. In general it may be said that the repair and maintenance costs of the furnaces mostly used, namely the Héroult, Girod, and Röchling-Rodenhauser, do not exceed those of the open hearth, as soon as heats averaging 3 tons and upwards are worked. In open-hearth furnaces this can be taken as 36 to 60c. per ton.

*The depreciation* is naturally higher, the more expensive the whole plant having the same capacity. It is therefore important

to use the plant as completely as possible, and the induction furnace undoubtedly allows this the most easily, as it works without rapid current variations. As this furnace moreover has undoubtedly the best working efficiency, and can be kept under current continuously, even during charging, without the machinery being in danger, there is a saving in time, and therefore an increase in production for a given size of furnace.

With an equal amount of total plant cost the depreciation per ton of steel with the induction furnace must be smaller than with other electric furnaces. In regard to the extent of the cost of plant itself, the first part of the book may be referred to.

*Electrode Costs.*—This comes into question only with arc furnaces. The conditions affecting the consumption of electrodes were treated in Chapter VI of the first part of the book. It was also proved in Chapter IX that the Girod and Héroult furnaces should be considered as working with the same electrode conditions, provided that both furnaces are technically of the same excellence. We can, therefore, without further thought put down the electrode consumption in these two furnaces as equally high. On the other hand the Stassano furnace, working under altogether different conditions, will give another electrode consumption. The electrode material will also naturally affect the cost per ton of steel. Carbon electrodes vary in price from $5.95 to $9.52 per metric ton; graphite electrodes, $15.47 to $53.20. Carbon electrodes can sometimes be produced considerably cheaper in one's own plant, but this presupposes very large electrode consumption and a very large electric furnace plant, otherwise the cost of one's own electrodes will be higher than that of those from a special plant.

It is perhaps not without value to consider that the mild steel pole pieces, such as are used in the Röchling-Rodenhauser furnaces, are not attacked. As is well known they are protected from the high temperatures of the bath by a conductor of the second-class, which is composed of the lining itself. Through this arrangement every electrode cost disappears.

Certain operating costs proceed from the auxiliary machinery

necessary with all furnaces. For instance, with the Röchling-Rodenhauser furnace there is the air cooling of the transformers, and with all arc furnaces a certain water consumption for cooling the electrodes, or for the governing of the electrodes as in the Stassano furnace. To this also belong the costs of the power necessary for the tilting or turning of the furnaces, and finally also that necessary for automatic regulation, etc. These costs altogether are, however, only very small. With all electric furnaces they only amount to a very few cents per ton. Finally a certain consumption of working tools, rabbles, rods, etc., should not remain unmentioned, which should cause about the same costs for all furnaces. Also when calculating the costs exactly, the power for lighting, operating the travelling cranes, etc., should be considered, which can be taken as equally high for the different furnaces. Finally, there is a license cost which comes into question, concerning the amount of which only the companies owning the patents can give information.

As a conclusion some operating costs may be given for different furnaces. It should be again pointed out that such figures and comparisons are to be used with the greatest care because they are based altogether on local conditions, and also on the kind of metal charged and obtained. In regard to the operating costs of the electric shaft furnace it has been pointed out already that it can only compete with the ordinary blast furnace under the most favorable conditions. These conditions exist, for instance, in some parts of the United States, Canada, Norway, Sweden, and Switzerland, and the following comparison of costs is for Sweden.

It has been made by Prof. von Odelstierna of Stockholm, and is taken from the *Electro Chemical and Metallurgical Industry*, 1909, p. 420.

In the charcoal blast furnace:

| | |
|---|---|
| 0.950 metric tons charcoal at $8.00 per ton | $7.60 |
| Labor | 1.00 |
| Repairs and general expenses | 1.50 |
| Per metric ton | $10.10 |

In the electric shaft furnace:

| | |
|---|---|
| 0. 270 metric tons charcoal | $2.16 |
| 0.3 electric h.p. years at $12.142 | 3.60 |
| Labor | 1.00 |
| 10 lb. electrodes at 3c. lb | .30 |
| Repairs and general expenses | 1.50 |
| Per metric ton | $8.56 |

According to these figures the use of the electric furnace gives a gain of about $1.54. It is based on the assumption that the Grönwall, Lindblad & Stalhane furnace, which has shown up the best so far, is taken as the electric shaft furnace. The ore taken for the comparison ought to contain 60% metallic iron, and the charcoal 83% carbon.

It is further assumed that both furnaces have the same output—from 8000 to 10,000 metric tons per year. The prices for ore and raw limestone* are not taken into consideration, as they depend so largely on local conditions.

If we compare the results found here with the previously given table of the cost of current for the electric blast furnace, we find complete agreement. For instance, from the table on page 230, we see that if the cost of heating in the two types of furnace is to be equally great the h.p. year should cost $12.18. This is with a production of (8 kg.), 17.637 lb. pig iron per h.p. day, and a price of coke of $7.61 per metric ton. The figures of Prof. von Odelstierna are based on power at $12.14 per h.p. year, charcoal at $8.09 per metric ton, and an output of 1 metric ton per 0.3 h.p. year. This corresponds to about (9 kg.), 19.841 lb. per h.p. day. If it is assumed that the coke and charcoal contain the same carbon then the estimate of von Odelstierna is calculated with a higher output and with a greater price for carbon, both of which points are favorable to the operating costs of the electric-blast furnace.

It should, however, be again pointed out that such favorable

* In the *Metallurgical and Chemical Engineering*, Feb., 1912, p. 71, LEFFLER says that in practise it has been found more economical to use unburned limestone, and that among other things burned limestone causes the burden to hang.

conditions for the electric-shaft furnace are not often present, so that it is restricted to countries poor in fuel and rich in ore and electricity.

In this respect it is, however, encouraging to note that, after the five months' test made at Trollhättan, ending April, 1911, (according to *The Iron and Coal Trades Review*, of Nov. 10, 1911), the pig iron produced per h.p. year equalled 3.79 metric tons or 22.92 lb. (10.41 kg.) per h.p. day; this corresponds to an output of 1 metric ton per .262 h.p. year. These later and better figures are the average of the first week's run after again starting up, and are attributed to the improved gas circulation, under the furnace roof which, according to Robertson, the inventors maintain that the important point is to make this furnace last as long as possible, and in order to do this they consider it absolutely necessary to have the roof cool. Richards suggests (A.E.S., April, 1912) that the arch of the furnace hearth be protected by water-cooled plates, as is common with open-hearth practise. This, however, as has already been suggested, may decrease the efficiency too much. Lyon states that attempts were made at the Noble Electric Steel Co. in California to preserve the roof of the crucible hearth by water-cooled plates embedded in the brickwork, but these did not prove especially effective. Leffler writes at this time that they would gladly dispense with the artificial gas circulation if they could. As is elsewhere mentioned, Leffler says that calcined limestone causes the burden to hang. Yet Noble, with his California furnace, says he only uses calcined limestone, and furthermore uses no artificial gas circulation.* In the last tests made at Trollhättan, the repairs and petty expenses cost about $1.60 per ton of pig iron produced. Part of these operating cost repairs are caused by the roof burning away. If half of the above amount were saved by the durability of the roof being increased, it would make, in a 2500 h.p. furnace, producing 25 tons daily, an annual saving of $350 \times 25 \times .80 =$ $7,000, enough to pay almost 9% on the investment.

* The reason the Trollhättan furnace has gas circulation and the Noble furnace none, is because the former is operated as an arc furnace, but the latter as a resistance furnace.

The cost of producing one ton of electric pig iron during the 5 months period ending in April, 1911, was estimated from the records and from a personal investigation given on the spot to be as follows:

| | |
|---|---|
| 1.52 tons of ore, 67.1% at $2.68 | $4.07 |
| .262 kw. year at $13.40 | 3.51 |
| 85. kg. (187 lb.) limestone at $1.61 per ton | .14 |
| 416 kg. (915 lb.) charcoal at $12 | 4.99 |
| 5.27 kg. electrodes consumed * at $67 | .36 |
| Labor | .78 |
| Repairs and petty expenses | 1.60 |
| Interest and sinking fund, 10% on $24,000 | .35 |
| Total | $15.80 |

The cost of producing one ton from hematite of 50% iron was $16.04. One of the Norwegian companies on the West coast, now (1912) constructing a plant for the smelting of 60% magnesite, estimated the cost per ton of iron, with electricity at $5.46 a kw. year, at $11.25, using English coke at $5.63 per ton.

For the Stassano furnace detailed cost figures are given by Osann in *Stahl und Eisen*, 1908, No. 19. They apply to the furnace described in Chapter VII for one-ton charges, making steel for castings from cold material. The figures are further based on the following special conditions. The furnace remains unused each night for three hours, and 24 hours on Sunday. During these times it is kept warm by electricity, the current being switched on for one-quarter of an hour, and off for three-quarters of an hour. Under this non-continuous operation the furnace gives 3.5 metric tons per day, or 840 metric tons per year of 240 working days.

The furnace takes three men per shift, the average wage being given as $1.19. The lining costs $95.24, exclusive of the labor, when magnesite is used. It must be renewed every three weeks, that is, after a production of about 63 metric tons, and requires 4 to 6 days for the renewal.

* The total electrodes used per ton of iron produced was 10.28 kg., the difference being attributable to the stub ends, now no longer prevalent, with the new screw type electrode.

The construction cost of the furnace is given as $8,750.

Under these conditions the following calculations are given per metric ton of fluid metal:

| | | |
|---|---|---|
| Depreciation | | $ 0.992 |

Cost of the charge:

| | | | |
|---|---|---|---|
| 1 | metric ton scrap at $15.95 | $15.952 | |
| .02 | metric ton mill scale at $4.047 | .081 | |
| .02 | " " lime at $2.857 | .057 | |
| .008 | " " 12% ferro-silicon at $35.71 | .285 | |
| .004 | " " 80% ferro-manganese at $52.38 | .209 | |
| .0008 | " " aluminum at $357.00 | .285 | |
| | | | 16.869 |

Cost of power:

| | | |
|---|---|---|
| For melting 900 kw. hrs. at 1.071c | $9.643 | |
| For heating during delays | 1.071 | |
| Cost of furnace, lining, and repairs | 2.619 | |
| Labor | 2.047 | |
| Electrodes | .595 | |
| Cooling water | .095 | |
| | | 16.070 |
| Total | | $33.941 |

According to a more recent article (Neumann, *Stahl und Eisen*, 1910, p. 1066) it is possible to greatly reduce the cost of the lining when using dolomite for the hearth. At the same time through the use of a purer charge the power consumption for melting drops to 750 kw. hrs., and because of the corresponding less work with slags the furnace can last 70 to 100 heats. Definite figures for the lowering in costs brought about in this way are not known.

Cost calculations for the Héroult furnace are similarly not known. On the other hand they have been published for the Girod furnace. The following are taken from *Stahl und Eisen*, 1908, p. 1825, and apply to a 2-ton furnace.

If a cold charge is worked, consisting of scrap, turnings, and pig iron, and completely refined to give steel of high value, the costs per metric ton are as follows:

| | |
|---|---|
| .1 ton lime, .1 ton ore, and additions of various alloys, from | $ .714 to $ .809 |
| Electrodes | .952 – 1.190 |
| Labor | 1.142 |
| Furnace maintenance, tools, etc | 2.857 |
| 1,000 kw. hrs., the cost depending on the price of power | ..... |

If melting, without further refining, is all that is necessary, that is to say a similar method of working to that recently carried out with the Stassano furnace at Bonn, then the following figures should be used:

| | |
|---|---|
| Lime, etc | $0.238 |
| Electrodes | .762 |
| Labor | .762 |
| Furnace maintenance, tools, etc | 2.285 |
| Power consumption, 750 kw. hrs | ..... |

For the refining of a liquid steel charge taken from the converter or open hearth, the following figures are given:

| | |
|---|---|
| .04 tons lime, and additions | $ .524 to $ .619 |
| Electrodes | .381 |
| Labor | .571 |
| Furnace maintenance, etc | .952 |
| Power consumption about 300 kw. hrs | ..... |

In these tables depreciation and the loss in operation have not been taken into consideration.

The latter is given by Borchers as 10 to 11%, who also says that the consumption of electrodes in the larger furnaces ought to amount to 0.012 to 0.015 metric tons per metric ton of steel with cold charges. This gives an electrode cost of $0.571 to $0.762 per metric ton. In regard to the life of the furnace it is stated that with cold charges the walls last about 80, and the bottom about 120 heats, the roof stands 25 to 30 heats with small furnaces and 20 to 25 with large ones.

The costs with the Héroult furnace will scarcely differ in an important degree from those of the Girod. As complete figures have not been given for the Héroult furnace the following partial results may be shown taken from *Metallurgical and Chemical Engineering*, 1910, p. 179. They apply to the 15-ton furnace at So. Chicago. Liquid Bessemer metal, of which the composition is not given, is refined in 12- to 14-ton charges, the final material containing 0.03% P. and 0.03% S. Power consumption 200 kw. hrs. per metric ton. The furnace roof of silica brick costs $60. It requires changing each Sunday.* With 12 heats a day, and 13 metric tons per charge, this equals $0.0642.

| | |
|---|---|
| Hearth repairs, about | $0.0642 |
| Lining costs, about | .1284-† |

This does not take into consideration the costs per ton of door bricks, which must be replaced at certain times. The electrode consumption is given as 6.6 lbs. per metric ton. Graphite electrodes are used, and the cost per ton of steel is about $1.50.‡

Neumann gives the loss with a cold charge as 6%, and 2.5 to 3% with fluid charges. With the same kind of charge, how-

* The roof problem has recently been the subject of careful study by FitzGerald (see A. I. E. E., June 25, 1912, transactions). A brick made of silicon carbide has been manufactured which it is believed will have a much longer life in the steel furnace than the silica brick now used. The brick is made by taking powdered or granular silicon carbide, mixing it with a suitable temporary binder, such as a solution of dextrine, molding and then heating in an electric furnace to the temperature at which silicon carbide is formed. Bricks made in this way have been used in the roof of an experimental steel furnace in one of these laboratories and then put to the severest test possible. The bottom of the furnace was purposely raised well above the normal level so as to bring the surface of the slag as close to the roof as possible, the actual distance in some experiments being only 10 in. (25.4 cm.). Then the furnace was worked at double the normal rate of generation of energy so that the heating of the roof was very intense, so much so that an ordinary silica roof would melt down rapidly and be completely destroyed in a single heat. Even under these very severe conditions the silicon carbide roof stood up perfectly. Experiments have also been made in other steel furnaces and these results confirmed. The most serious objection to a roof of this kind is its relatively great cost, but if it lasts a sufficiently long time it is nevertheless economical.

† Dolomite taken at $6.00 per metric ton.

‡ This applies to electrodes of Acheson graphite, costing 50 cents per kg.,

ever, the same loss is to be expected in both the Héroult and Girod furnaces.

A certain difference in the operating costs of the Héroult and all other electric furnaces arises from the fact that the former uses carbon for deoxidation instead of ferro-silicon. With normal heats, therefore, and deoxidation with carbon the Héroult furnace has to figure on a consumption of about 4 kg. ferro-silicon per metric ton; in the case of other furnaces, and the Héroult also, if deoxidation with carbon is not followed, on about 7 kg. If it is assumed that the Héroult uses 3 kg. petroleum coke, then the following figures are given for deoxidation and desulphurization:

| | |
|---|---|
| Héroult furnace, using 3 kg. petroleum coke at $1.90 | $0.057 |
| Héroult and all other furnaces using 3 kg. ferro-silicon at 7.26c | .216 |
| So that deoxidation and desulphurization by means of ferro-silicon alone is dearer than that by carbon and ferro-silicon by about | .159 |

As mentioned before, this has the advantage, however, that it does not influence the composition of the bath, and so is often used even in the Héroult furnace.

There remains finally the operating costs of the Röchling-Rodenhauser furnaces. Such figures have been published by *Wedding*. The following apply to a 5-ton furnace working on fluid charges:

| | |
|---|---|
| Power consumption 230–280 kw. hrs. per metric ton | |
| Additions, about | $0.536 |
| Lining costs, using magnetite | .595 |
| Wages | .178 |
| Air for cooling transformers | .050 |

such as are used in this furnace. Up to within a short time it was impossible to construct satisfactory electrodes of carbon for the 15-ton Héroult furnace. This is emphasized by T. W. Robinson's discussion before the American Iron & Steel Institute, May, 1912, where he says: "Our necessities represented a requirement that the electrode manufacturers of America and Europe had not been called upon to meet, and it took much time and money before there was finally accomplished the 20-inch round amorphous carbon electrode that is now being used" (in the 15-ton Héroult furnace).

A 2-ton furnace using polyphase current gave the following costs, when scrap was worked up for making steel castings:

Charge

| | | | |
|---|---|---|---|
| 1 metric ton scrap | | | $15.952 |
| 5% loss | | | .798 |
| .01 metric ton roll scale | (22. lb.) | | .040 |
| .035 " " lime | (77. lb.) | | .100 |
| .005 " " fluor-spar | (15.7 lb.) | | .074 |
| .01 " " sand | (22. lb.) | | .014 |
| .004 " " ferro-manganese | ( 8.8 lb.) | | .209 |
| Loss in ferro-alloys remaining behind | | | .157 |
| | | | $17.344 |
| Power consumption, about 900 kw. hrs., price varies. | | | |
| Lining and repair costs | | | .636 |
| Labor | | | .793 |
| Air for cooling transformers at 1.071c. per kw. hr | | | .079 |

These figures are given for a 2-ton furnace which, working with cold charges, allows a production of 6 to 8 tons per day. Apart from this it should be mentioned that the lining and repair costs when dolomite is used, and liquid charges, only amount to 0.238 to 0.428c. with 3- to 8-ton furnaces.

It may be mentioned again that all the cost figures given above are only exactly correct for certain predetermined local conditions. Care should, therefore, be taken in using them for comparison. The weight of material used ought to be shown, and the kind of charge and the final metal required have a great influence.

The consideration of the different factors affecting costs given in the first part of the book appear, therefore, to be very valuable, and this part may once again be referred to.

## B. THE ELECTRO-METALLURGY OF IRON AND STEEL

### INTRODUCTION

UNTIL the invention of the steam-engine the operation of an iron and steel plant required the presence of a waterfall as the source of power for the hammers and blast. If, at the same time, sufficient ore beds and forests were in the neghborhood all the requirements were filled for the prosperity of the plant. The consumption of iron and steel tools was moderate, the plants could operate economically in a modest way and with small water-powers, for with the absence of railroads, etc., the products found a paying market in the immediate vicinity, and the bringing in of foreign goods was almost impossible. The few specially large German water-powers were not needed, and would not be used because the technical knowledge necessary was not sufficiently advanced.

Conditions changed as the supply of charcoal began to decrease and the consumption of iron and steel to increase, for the old plants with their associated water-powers and limited amounts of charcoal could only increase their production to a certain amount. The knowledge that ores could be smelted with coke, and the invention of the steam-engine, made it possible to use commercially the immense stores of energy lying dormant in the earth in the form of coal. Soon the plants deserted their old places near the waterfalls, and changed their locations to the coal-fields, where fuel and therefore power were present for application in unlimited amounts.

Then succeeded the remarkable newer growth of the iron and steel industry with its attendant immense production.

But the consumption of iron and steel constantly increases, coal begins to decrease in amount and become more expensive, and the industry will soon be forced, as in the time of our fathers, to look for a new and constant source of power. Electric energy

is the first to come into consideration, since it is possible to produce it from coal at a moderate cost. Also the railroads have brought the most remote countries into connection, and the enormous water-powers of foreign lands can be used as sources of cheap electric power. Is it to be wondered at that many technical men are working at the problem of the building of electric furnaces, or that this task should soon be solved economically, when it is known that electric heating produces a higher furnace efficiency than heating with fuel?

So we see efforts being made recently to build plants near the larger water-powers, as in the old days, in order to obtain electric power at the lowest cost, and to produce iron and steel from ore by electricity.

Also in the industrial countries the electric furnace is gaining importance from day to day, for it is proving capable of producing higher quality steels equal to crucible steel, from impure raw material.

It is the authors' wish that the production of iron and steel by electricity may receive such an impulse that the statements in this little book will very soon be exceeded by the facts.

GLÜCK AUF!

**J. SCHOENAWA.**

## THE ELECTRIC SMELTING OF IRON ORES FOR IRON AND STEEL PRODUCTION

The usual commercial process by which pig iron is produced is smelting in a blast furnace with fuel, flux and a blast of air. In the upper part, or shaft, of this furnace a continuous series of thermal and chemical reactions take place, which reduce the iron and prepare it for its final smelting in the hearth. These preliminary reactions could, if desired, be carried on in a special shaft into which ore is charged and subjected to the action of the hot furnace gases.

In the lower part, or smelting zone, of the furnace the reduced and partially carburized iron is melted; the impurities of the ores and fuel are fluxed with the flux added for this purpose, and thereby converted into a liquid cinder, or slag. Besides these thermal effects, some chemical reactions occur which the temperature in the shaft was not sufficiently elevated to effect, such as the reduction of the oxides of silicon, manganese and phosphorus (the reduced elements being then absorbed by the iron), the conversion of iron sulphide in part to calicum sulphide, etc.

First let us collect the data upon which to base a study of these reactions. Such data are given below; some of them have not been wholly confirmed experimentally, yet the estimated values are close enough to afford calculations of practical value:

1 kw. hr. = 864.5 cals.
1 kw. hr. = 1.34 h.p. hrs.
1 h.p. hr. = 0.746 kw. hrs.
Spec. ht. of iron = 0.20.
Spec. ht. of blast furnace slags = 0.30.
Spec. ht. of ore = 0.20.
Spec. ht. of CO = 0.243.
Spec. ht. of C = 0.20.
Spec. ht. of air according to its weight = 0.30.
Latent heat of fusion of pig iron = 46 cals.
Latent heat of slag = 30 cals.

PLATE I.

Test pieces of seamless drawn electric steel tubes (Röchling). The normal tube, and test pieces made from it in the cold state.

## TABLE I

| | With the Reduction of 1 Kg. of Reduced Material | | | | | | |
|---|---|---|---|---|---|---|---|
| | is necessary | | is obtained | | heat required | | |
| | C. kg. | CO kg. | CO kg. | $CO_2$ kg. | Gain cals. | Loss cals. | Balance cals. |
| $FeO+C=Fe+CO$.. | 0.214 | ..... | 0.500 | ..... | 529 | 1,332 | − 803 |
| $FeO+CO=Fe+CO_2$ | (0.214) | 0.500 | ..... | 0.786 | 1,200 | 1,332 | − 132 |
| $Fe_3O_4+4C=3\,Fe+4CO$..... | 0.286 | ..... | 0.667 | ..... | 707 | 1,648 | − 941 |
| $Fe_3O_4+4\,CO=3Fe+4CO_2$..... | (0.286) | 0.667 | ..... | 1.048 | 1,603 | 1,648 | − 45 |
| $Fe_2O_3+3C=2\,Fe+3CO$..... | 0.321 | ..... | 0.75 | ..... | 795 | 1,876 | −1081 |
| $Fe_2O_3+3CO=2Fe+3CO_2$..... | (0.321) | 0.75 | ..... | 1.178 | 1,802 | 1,876 | − 74 |
| $MnO_2+2C=Mn+2CO$..... | 0.436 | ..... | 1.017 | ..... | 1,078 | 2,209 | −1131 |
| $Mn_3O_4+4C=3Mn+4CO$..... | 0.291 | ..... | 0.679 | ..... | 719 | 1,947 | −1228 |
| $MnO+C=Mn+CO$..... | 0.218 | .509 | 0.509 | ..... | 540 | 1,817 | −1277 |
| $SiO_2+2C=Si+2CO$ | 0.857 | ..... | 2.00 | ..... | 2,119 | 7,829 | −5710 |
| $P_2O_5+5\,C=2\,P+5CO$..... | 0.968 | ..... | 2.258 | ..... | 2,394 | 5,966 | −3572 |

To reduce 1000 kg. of iron from magnetite requires 1381 kg. of ore. For simplicity the ore may be considered as pure $Fe_3O_4$ without any earthy constituents which have to be slagged off. Reduction with pure carbon then takes place according to the following equation: 232 kg. $Fe_3O_4$ + 48 kg. C = 168 kg. Fe + 112 kg. CO. The CO therefore measures $4 \times 22.4 = 89.6$ cu. metres. For the production of a metric ton, 1000 kg. of pure iron 286 kg. of carbon are necessary and 533 cu. m. of carbon-monoxide are produced.

In the blast furnace much larger amounts of carbon than these theoretical calculations call for are required, because carbon is depended upon not only to reduce the ore, but also to furnish the heat required for the process. According to the

equation $Fe_3O_4 + 4C = 3Fe + 4CO$, the process can be carried out without the blast being used if the amount of heat is supplied which the table shows is necessary. The amount of gas produced by the reduction would be only about one-tenth of that produced in the blast furnace for the same weight of iron, for in the latter case the gas is diluted with a large nitrogen content.

If magnetite is mixed with carbon in the proportion calculated above, and the mixture heated by electricity to the necessary reduction temperature as well as to the melting temperature of about 1300° C., reduction of the magnetite takes place readily. The following rough calculation gives the theoretical power consumption necessary for the production of 1 metric ton of iron in a condition fluid enough to be readily tapped, which is necessary in practise.

| | |
|---|---|
| 1381 kgs. ore heated to 1300° C. = 1381 × 0.2 × 1300 = ... | 359,060 cals. |
| 286 kgs. carbon heated to 1300° C. = 286 × 0.2 × 1300 = | 74,360 " |
| 1000 kgs. iron heated to reducing temperature 1000 × 941 = | 941,000 " |
| 1000 kgs. iron melted = 1000 × 46 = ..... | 46,000 " |
| | 1,420,420 cals. |

This corresponds to $\frac{1420420}{864.5} = 1643$ kw. hrs.

From this it is clear that the process requires much less carbon than the blast furnace if considerable electric energy is supplied. In the same manner a high-carbon iron can be produced if sufficient carbon be supplied not only to reduce the ore, but also to supply that which dissolves in the metal. A rough calculation for an iron with 3% carbon is given below:

The carbon required is 286 + 30 = 316 kg., and 1030 kg. of pig iron is produced.

| | |
|---|---|
| 1,381 kg. ore heated to 1300° C. ..... | 359,060 cals. |
| 316 kg. carbon heated to 1300° C. ..... | 82,160 " |
| 1,000 kg. iron to the reducing temperature..... | 941,000 " |
| 1,030 kg. iron melted..... | 47,380 " |
| | 1,429,600 cals. |

This corresponds to $\frac{1429600}{864.5} = 1653.7$ kw. hrs. per 1030 kg. iron, which equals 1605.5 kw. hrs. per metric ton.

It should be remembered that the figures given for the coke consumption in the blast furnace take in all losses through cooling, radiation, etc., and in this respect the efficiency of the blast furnace is not bad.

The power consumption given, on the other hand, is only the theoretical minimum, in operation it will be considerably higher, depending on the type of furnace used and its efficiency, etc. Also the figures for carbon consumption are for chemically pure material, while in operation fuel containing ash has always to be figured on so that the minimum carbon consumption in the form of coke, charcoal or similar material is correspondingly higher.

The economical side of the smelting of ores by means of the carbon theoretically necessary for reduction and electrical energy to supply the heat for the thermal reactions requires that the saving in coke in the new process must be greater than the expense of the necessary electrical energy.

As a result the process has prospective use only under conditions where ore and power are cheap and coke is dear, as in some parts of Canada, Italy, Norway, Sweden, California, etc.

The use of coke can be completely done away with and the iron separated from the ore electrolytically like aluminum, but the necessary power consumption is so extremely high that this method does not appear economical even for the future. Recently proposals have also been made to use iron pyrites as the raw material for smelting iron in the electric furnace. It is to be melted and air-blown through the bath until a considerable amount of ferrous oxide has been formed; then the blast stopped, and the bath allowed to react according to the equation:

$$FeS + 2\,FeO = 3\,Fe + SO_2$$

It is scarcely possible that the process will have a great future.

The process given above of using just enough fuel to combine with the oxygen of the ore and electric heating of the ore-fuel mixture forms the basis of the many recent attempts to smelt iron ore by electro-thermal methods.

It should be emphasized that, in electro-thermal processes,—as the words themselves indicate,—the electricity serves only as the source of heat which brings the charge to the temperature required for reduction and melting. Electrolytic processes—where electricity is used both as a source of heat and as a reducing agent—are less often employed because only direct current can be used. In regard to this, we may refer again to Part I.

Electrical heating of the charge gives the great advantage that, because of the much lower fuel consumption, the influence of the latter on the charge and melted material can be regulated much better, and the operation can be carried out if desired at higher temperatures than used up to now in the blast furnace. This has a great metallurgical advantage for, as is well known, the "reaction ability" of all material increases considerably with increase in temperature.

In general it is to be expected that in the smelting of the ordinary iron ores which contain more or less manganese, sulphur, phosphorus, silica, etc., the same reduction reactions will take place as are already known for the blast furnace process, etc., and that with electric smelting an iron of a certain determined purity and analysis will be obtained by regulating the furnace temperature and the slag. The iron will be very low in sulphur, for experience shows that the slagging off of the sulphur is favored by high temperatures, and with the electric furnace the temperature can be raised to any desired amount. Smelting in the electric furnace can also be carried on in such a way that, according to the amount of reducing material used, an iron can be produced of any desired carbon content, even practically free from carbon. However, it is a question whether it is preferable to produce right away a soft material, or to make a higher carbon product and suitably refine this later by special processes. Concerning this, local conditions alone can lead to a decision.

In smelting lean iron ores, more electric energy is required,

because the impurities have to be heated to the full temperature of the charge, and, furthermore, additional flux must be added to slag off these useless impurities, and the extra slag must also be heated to the temperature of the furnace. All this waste makes the process correspondingly more expensive.

Raw spathic ore, brown iron ore, etc., must be calcined when smelted, which also requires electrical energy and correspondingly increases the cost. In conclusion: the electric production of iron, which is indeed an "infant industry," must be accomplished without the loss of an unnecessary kilowatt in order to successfully compete with the old economically working blast furnace.

In general, therefore, at present usually high percentage iron ores, preferably magnetite and red hematite, are smelted electrically. If it happens that poorer ores have to be used, then they must be previously carefully prepared and concentrated. During this concentration it is well to remove as completely as possible any pyrites, apatite, etc., which may be present, and thereby help in the production of a highly valuable iron of great purity similar to Swedish or Styrian, which will be suitable for the production of high quality steels. The fuel must also be as low as possible in ash, so that the slag volume is not increased too much. The size of the material is of secondary importance for suitable reduction, but very fine materials are not willingly used exclusively because of the difficulty of removing the gases produced in reduction.

In the first tests carbon and ore were intimately mixed, pressed together with tar and used in the form of briquettes. This briquetting is unnecessary and can be more readily rejected as it is costly, for in those countries where electric smelting is commercially possible because of dear coke the price of tar is also correspondingly high.

Electric smelting of iron ore can be carried on in electric steel-making furnaces. The mixture for reduction will either be charged altogether, or else added little by little, depending on the type of furnace. If a pool of liquid pig iron has formed on the hearth, then the reduction of the ore mixture will progress more quickly, for the carbon of the liquid metal takes an energetic

part in the reduction. The fluid pig iron will then have to be recarburized to the required amount by the carbon of the charge.

In regard to the necessary power consumption, that type of furnace will work most favorably with which the radiation loss is the smallest.

The Stassano furnace, to the construction of which the first part of this book is devoted, heats the mixture by radiation, for the arcs are outside of the material to be heated. But, as the arcs radiate heat in all directions, and only that much which radiates downwards is used economically, it is to be expected that the efficiency of this furnace will be proportionately low. On the other hand, the electrode consumption will not be very high for the electrodes are not in contact with the charge, and so will not be attacked by the iron ore.

1. **Smelting of Ore in the Stassano Furnace.**—(The charge heated by radiation from the arc.) Neumann and Goldschmidt have published results of the following smelting test (*Stahl und Eisen*, 1904, pp. 687, 885). The analyses of the materials used were:

*Ore:*

| | | | |
|---|---|---|---|
| $Fe_2O_3$ | 93.02% | P | .056% |
| MnO | .62 | CaO+MgO | .5 |
| $SiO_2$ | 3.79 | $H_2O$ | 1.72 |
| S | .058 | | |

*Lime:*

| | | | |
|---|---|---|---|
| CaO | 51.21% | $Fe_2O_3$ | .50% |
| MgO | 3.11 | $SiO_2$ | .90 |
| $Al_2O_3$ | .50 | $CO_2$ | 43.30 |

*Charcoal:*

| | | | |
|---|---|---|---|
| Carbon | 90.42% | Ash | 3.88% |
| Water | 5.70 | | |

*Pitch:*

| | | | |
|---|---|---|---|
| Carbon | 59.20% | Hydrocarbons | 40.50% |
| Ash | .27 | | |

Briquettes were made from a mixture of 1000 kg. ore, 125 kg. lime, 160 kg. charcoal, 120 kg. pitch (charcoal and pitch together

containing 230 kg. carbon). These briquettes constituted the charge. According to Stassano the heat requirements per 100 kg. ore in the charge are calculated as follows, the data below being chosen from his tables.

| | |
|---|---|
| Decomposition of the oxide of iron $\frac{93.02 \times 192}{0.16}$ | = 111552.000 |
| Vaporizing the moisture in the ore and charcoal $(1.72 + 1.21)\,637$ | = 1866.41 |
| Calcining the flux $12.5 \times 425$ ..... | = 5312.5 |
| Heating the $CO_2$ to 500° C. $\frac{5.429 \times .016 \times 500}{.044}$ | = 987.09 |
| Heating the CO produced $\frac{20.9}{.012} \times .0068 \times 500$ | = 5921.667 |
| Melting the iron produced $65 \times 350$ ..... | = 22775.2 |
| Melting the slag produced $13.89 \times 600$ ..... | = 8334.0 |
| | 157311.427 |
| Produced from the burning of C to CO $20.9 \times 2175$ | 45457.500 |
| Leaving ..... | 111853.927 |

These 111,853.927 calories correspond to 129,386 kw. hr. From 100 kg. ore 65.114 kg. of iron will be reduced, so that the power required per metric ton of iron is 1987.6 kw. hrs. This power requirement is, however, only calculated theoretically, and figures concerning the real power consumption have not been published; however, as shown above, the radiation loss with the Stassano furnace must be considerable.

An idea of the amount of this radiation loss is obtained from a further test published by Goldschmidt in which the power consumption is given. In this test 70.25 kg. of the same briquettes used in Test No. 1 were smelted in a 100 h.p. furnace. The output was 30.8 kg. iron with a power consumption of 97.2 kw. hrs. = 132.2 h.p. hrs. The theoretical power consumption for the charge may be calculated on the basis of the analyses given above as follows:

For the reduction of the iron contained in the final product were necessary $\frac{30727.312}{112} \times 192$ ..... = 52730.262

For the reduction of the manganese in the final product were necessary $\frac{28.336}{55} \times 94.6$ ..... = 48.719

For melting the metal $30.8 \times 350$ ..... = 10780.00

For melting the slag $6.3 \times 600$ ..... = 3780.000

For heating and vaporizing the moisture $1.316 \times 637$ ..... = 838.292

For calcining the lime $6.25 \times 475$ ..... = 2968.750

For superheating the steam to 500°,

$1{,}316 \times 400 \times .48$ = 252.672

For superheating the $CO_2$ to 500° C,

$\frac{2.714 \times 500 \times .016}{0.44}$ = 493.554

For superheating the hydrocarbons to 500°

$2.43 \times 500 \times .27$ ..... = 328.05

For superheating the CO produced

$\left\{\frac{3 \times 30727 \times 312}{112} + \frac{28.336}{55}\right\} \times 500 \times .0068$ ..... = 2800.131

Total 75020.330

From the combustion of the C to CO were produced

$9.883 \times 2175$ ..... = 21495.525

Leaving ..... 53524.805

As the whole charge consumed 97.2 kw. hrs. = 84012.072 cals., the heat efficiency was:

$\frac{53524.805 \times 100}{84012.072}$ ..... = 61.33%.

The power consumed per metric ton of iron reduced from its ore is shown to be 3123 kw. hrs. Unfortunately the analysis

of the metal produced is not given, nor the length of time of the test. The demonstrated efficiency of 61.33% is not very difficult from the calculated figure. It must be admitted that not only was this a test melt, but that several of the figures calculated gave accidentally very favorable results. In operation the efficiency would undoubtedly be much smaller, for the careful supervision possible with a small test would be lacking.

Because of the great heat radiation in the furnace which principally attacks the roof, the life of the roof must be small, and the economical carrying on of the process depends in the first place on the durability of the furnace. In order to make the roof somewhat more durable, either the whole or at least that part attacked the most must be protected by water cooling. This water cooling, however, apart from its complexity will bring about important heat losses, the amount of which will be gone into further in another place.

The power consumption per metric ton of iron is seen to be high as was to be expected. Theoretically it is 1643 kw. hrs. or 2680 with a furnace efficiency of 61.33%, compared with a proved figure of 3123. This increase in practise of 443 kw. hrs. is due to the use of ore which is not theoretically pure, and the consequent melting of the slag produced, the burning of the lime, vaporizing the water, etc., a proof that only ores as pure as possible should be smelted. With the smelting of more impure ores the power consumption would naturally be considerably higher yet. This high power consumption is due to the great radiation loss of this type of furnace, and can therefore scarcely be lessened. Further disadvantages are that no continuous operation is possible, and only small heats can be produced. From this it is evident that furnace types in which, like the Stassano, the charge is only heated by radiation can not be considered in the economical smelting of ore.

**2. Ore Smelting in Electric Hearth Furnaces.**—(Electrodes introduced into the charge.)

Theoretically these furnaces should work well because the charge so nearly surrounds the arc that the heat radiated is

completely absorbed. In operation, however, such a total absorption is impossible, the charge can only surround the arc to a limited extent, and the temperature is so high that radiation through the charge to the walls of the furnace is unavoidable. With such furnaces the lining and the special roofs, if such are present, are particularly strongly attacked by the "stagnant heat," so that it is impossible to maintain continuous operation. Also the electrode consumption will be high, for the electrodes are in contact with the ore mixture and will be attacked.

Many ore-smelting tests have been carried out with different types of furnace in recent years in order to remedy the trouble resultant upon the attack on the furnace walls, but with uncertain results. In every case the power consumption has been much more favorable than was expected, so that in this respect the question of electric smelting of ore would have been long since settled if a furnace construction had been found more suitable for continuous operation. The most recent tests of this kind have been carried out by Messrs. Grönwall, Lindblad & Stalhane, the latest test furnace being shown by figs. 124, 125 and 126, invented by the same men. One metric ton of white iron was produced in 1909 with 0.25 h.p. years equals 2190 h.p., that is $\frac{2190}{1.35}$ = 1622 kw. hrs., a result that closely approaches the theoretical minimum, and is to be explained perhaps by the very pure ore smelted. Further tests made with the Grönwall, Lindblad, Stalhane furnace are given elsewhere in Chapter XIII, under "Operating Costs," and under *B*, "Electro-metallurgy of Iron."

### THE SMELTING OF ORE IN THE INDUCTION HEARTH FURNACE, SYSTEM RÖCHLING-RODENHAUSER

The efficiency of this furnace will not be bad for smelting ore, notwithstanding that the charge is only heated by the heat of the molten bath, because the bath is covered with cold charge and the radiation from the lower part of the furnace can be kept low by means of suitable brickwork, etc.

Above everything else, however, because of the cooled upper surface of the bath due to the covering of the charge, and the heat-

ing from within, the roof will show great durability, which is a very important point, if there is to be continuous operation. Those furnaces which work with electrodes and have a roof are compelled to use extensive water cooling, sometimes in order to increase the life of the furnace. Through the avoidance of water cooling, a source of considerable loss of heat is avoided, so that the induction furnace is worthy of serious investigation for the smelting of ore.

Many smelting tests have been carried out in the Röchling-Rodenhauser furnace, and some reports of them may be given, for up to the present scarcely any results of ore smelting in the induction furnace have been published. High sulphur magnetite in a very fine state of division was used and high sulphur coke breeze, in order to produce a pig iron with 2.6 to 3.0% carbon, and as low in sulphur as possible. Although it was assumed that a greater part of the sulphur would pass away as gas due to the following reaction:

$$FeS + 2\,FeO = 3\,Fe + SO_2,$$

yet, by way of precaution, the theoretical amount of lime necessary to combine with the sulphur as sulphide of calcium was added to the charge, together with that necessary for the acid gangue, etc. The amount of slag produced in this way was not needlessly increased, although the CaS produced requires a large amount of slag for solution if it is hoped to produce a sufficiently good desulphurization in this way.

Analysis of the ore:

| | | | | |
|---|---|---|---|---|
| $Fe_3O_4$ | 96.38% | = 69.79% Fe | } 70.45% Fe. | |
| $FeS_2$ | 1.41 | = 0.66% Fe | | |
| $Mn_3O_4$ | 0.25 | = 0.18% Mn. | | |
| $SiO_2$ | 0.60 | | | |
| $P_2O_5$ | 0.05 | = 0.02% P. | | |
| CaO | 0.10 | | | |
| MgO | 1.21 | | | |
| | 100.00 | | | |

Oxygen combined with Fe & P = 26.62%.
Total sulphur in the ore = 0.75%.

**ANALYSIS OF THE COKE BREEZE**

| | |
|---|---|
| Carbon | 87.48% |
| Sulphur | 1.068% |
| Ash | 10.4% |

The principal constituents of the coke ash were:

| | |
|---|---|
| $SiO_2$ | 40.6 % |
| CaO | 5.6 % |
| Fe | 11.6 % |
| $Al_2O_3$ | 25.40% |

Oxygen combined with iron = 5.0%.

The carbon-monoxide produced passes away unused.

**Chemical Balance Sheet.**—100 kg. ore (1/10 of a metric ton) = 70.45 kg. iron. This requires:

(*a*) For reduction and combination of the 26.62 kg. oxygen,

$$C + O = CO$$

$$16\,O + 12\,C = 28\,CO$$

$$\frac{26.62 \times 12}{16} = 19.97 \text{ kg. C}$$

and produce $\frac{26.62 \times 28}{16} = 46.58$ kg. CO

(*b*) 70.45 kg. Fe carburized to 3% require

$$\frac{70.45 \times 3}{97} = 2.18 \text{ kg. C}$$

(*c*) 0.75 kg. S combined with CaO to form CaS require:

$$S + CaO + C = CaS + CO$$

$$32 + 56 + 12 = 72 + 28$$

$$0.75 \text{ kg. S} + 1.28 \text{ kg. CaO} + 0.28 \text{ kg. C} = 1.70 \text{ kg. CaS} + 0.70 \text{ kg. CO}$$

The total amount of carbon is therefore 19.97 + 2.18 + 0.28 = 22.43

corresponding to $\frac{22.43 \times 100}{87.48} = 25.65$ kg. coke breeze.

As, however, the ash of the coke also requires a small amount of carbon for the reduction of its metallic oxides, the calculations should be made with 25.80 kg. of coke breeze. This 25.80 coke breeze contains $0.258 \times 1.068 = 0.28$ kg. sulphur which must be slagged off as CaS.

0.28 kg. S + 0.49 kg. CaO + 0.10 kg. C = 0.63 kg. CaS + 0.24 kg. CO.

25.80 kg. coke breeze contains

$$\frac{10.4 \times 116 \times 25.8}{10000} = 0.31 \text{ kg. Fe,}$$

and

$$\frac{10.4 \times 5 \times 25.8}{10000} = 0.13 \text{ kg. O, in the form of oxide of iron.}$$

$$16\,O + 12\,C = 28\,CO \text{ or}$$

$$0.13\,O + 0.10\,C = 0.23\,CO$$

100 kg. ore therefore require

22.43 + 0.10 + 0.10 = 22.63 kg. carbon or

$$\frac{22.63}{27.48} = 25.87 \text{ kg. (57.03 lbs.) coke breeze.}$$

THEORETICAL AMOUNT OF SLAG PER 100 KG. ORE SMELTED

| From the ore | | From the coke ash | |
|---|---|---|---|
| | | $0.2587 \times 10.4 = 2.69$ kg. | |
| $SiO_2$ | 0.60 kg. | $SiO_2$ | 1.09 kg. |
| CaO | 0.10 kg. | CaO | 0.15 kg. |
| MgO | 1.21 kg. | $Al_2O_3$ | 0.69 kg. |
| | 1.91 kg. | | 2.69 kg. |

from this must be taken $0.166 \times 10.4 \times 0.2587 = 0.44$ kg. $Fe_3O_4$, leaving 2.69 − 0.44 = 2.25 kg. slag.

CaS produced 1.70 + 0.63 = 2.33 kg.

Lime addition for combining with the sulphur 1.28 + 0.49 = 1.77

Lime addition for slag..... 1.41

Total lime addition..... 3.18

The theoretical total amount of slag is 1.91 + 2.25 + 2.33 + 3.18 = 9.67.

In calculating the amount of carbon necessary for reduction, it must be remembered that before the beginning of the test the furnace was filled with 1000 kg. of refined Basic Bessemer metal, which latter had to be recarburized to the required amount. After this the following mixture was charged:

597.5 kg. ore + 183.5 kg. coke breeze + 19.0 kg. lime = 800 kg.,

compared with the theoretical amount which does not consider the recarburization of the refined Bessemer metal:

597.5 kg. ore + 154.6 kg. coke breeze + 19.0 kg. lime.

The Bessemer metal had a temperature of 1650° C. The ore was charged as uniformly as possible, and in comparatively large amounts. Care was taken that the bath was always covered with the mixture in order to keep the radiation loss as low as possible; a method of working that, in general, was not hard to maintain.

The slag produced during the tests was only removed once, and the exact amount was obtained. As the furnace used for the tests was mounted on a scale, the weight of the Bessemer metal charged and the finished material were also obtained exactly. The smelting of the 800 kg. of charge required 1030 kw. hrs.

### MELTING RESULT

**(a) Output of Slag.**

99 kg. slag with 9.12% FeO = 7.09% Fe and 2.60% S. Theoretically the slag should contain:

1. From the charge 9.67 × 5.975 = 57.78 kg... 57.78 kg. slag.
2. Lime for slagging (3.18 − 1.77) = (1.41 × 5.975) = ..... 8.42 kg. slag.
3. Excess of coke breeze = ..... 3.00 kg. slag.
4. Slag remaining in furnace from previous heat = ..... 20.8 kg. slag.

Weight of slag = ..... 90.00 kg. slag.

The weight of this slag is increased by its iron contents

$$\frac{90 \times 100}{100 - 9.12} = 99 \text{ kg. which contains}$$

$$\frac{7.09 \times 99}{100} = 7.02 \text{ kg. iron.}$$

**(b) Output of Iron.**

1000 kg. of Basic Bessemer was charged containing:

C .06% P .093% S .073%,

1427 kg. electric pig iron were tapped with 2.64% C, 0.02% Si, 0.073% P, 0.076% S, of which 1427 − 1000 = 47 kg. were produced from the mixture. The theoretical amount is—

(1) From the ore $5.975 \times 0.7045 = 420.94$

(2) From the coke ash,

$$\frac{1.835 \times 11.6 \times 10.4}{100} = \text{kg. iron} = \frac{2.20}{423.14}$$

From this kg. iron $= \frac{7.02}{416.12}$ went to the slag.

This weight when calculated to electric pig iron equals

$$\frac{416.12}{0.9736} = 427 \text{ kg.}$$

The loss of metal in the slag is therefore $\frac{7.02}{4.2314} = 1.6\%$.

**CHEMICAL BALANCE**

**(a) The Carbon.**

| | | |
|---|---|---|
| 1,000 kg. Basic Bessemer metal with 0.06% C. carburized to 2.64% C. require (2.64 − .06) 1,000 = ... | 25.8 | kg. C. |
| 427 kg. electric pig iron contain 427 − 416.12 = ..... | 10.88 | " " |
| The reduction process requires 5.975 × 19.97 = ..... | 119.32 | " " |
| The formation of CaS requires (0.28 + 0.10) 5.975 = .. | 2.27 | " " |
| The reduction of the iron oxide in the coke ash requires 0.10 × 5.975 = ..... | 0.98 | " " |
| | 159.25 | kg. C. |

As 87.48 kg. C = 100 kg. coke breeze, this 159.25 kg. C = 182.0 kg. coke breeze.

**(b) The Sulphur.**

*Brought in:*

| | |
|---|---|
| 597.5 kg. ore at 0.75% S = | 4.48 kg. S |
| 183.5 kg. coke breeze at 1.068 S = | 1.96 " |
| 20.8 kg. slag held back containing 1.0% S = | 0.21 " |
| | 6.65 kg. S |

*Taken out:*

| | |
|---|---|
| 99 kg. slag at 2.6% S = | 2.57 kg. S |
| 427 kg. electric pig iron at 0.076% S = | 0.32 " |
| | 2.89 kg. S |

Therefore 6.65 − 2.89 = 3.76 kg. S or 56% of the total sulphur was gasified.

**(c) Phosphorus.**

| | |
|---|---|
| 1000 kg. Basic Bessemer metal at 0.093% P = | 0.93 kg. P |
| 597.5 kg. ore at 0.02% P = | 0.12 " |
| P brought in | 1.05 kg. P |
| 1427 kg. electric pig iron at 0.073 need = | 1.05 kg. P |

**(d) The Furnace Gases.**

$$12\,C + 16\,O = 28\,CO$$

| | | |
|---|---|---|
| Therefore (119.32 + 2.27 + 0.98) = 122.57 kg. C + 163.43 kg. O = | 286.0 | kg. CO |
| 183.5 − 182.0 = 1.5 excess coke corresponds to 1.31 C. This was charged in excess, burned with air gives | 3.05 | kg. CO |
| The burning takes place with 1.74 kg. O, that bring in | 6.54 | kg. CO |
| The total gas made is | 295.59 | kg. |

HEAT BALANCE

The furnace was held at 1300° C. during the test, and the iron tapped at the same temperature. The mixture for reduction, therefore, had to be first heated to this temperature after charging.

### 1. Heat Expended.

| | |
|---|---|
| 1. 597.5 kg. ore require $597.5 \times 1300 \times 0.20 =$ ..... | 155,350 cals. |
| 2. 183.5 kg. graphite, $183.5 \times 1300 \times 0.23 =$ ..... | 48,426 " |
| 3. 19.0 kg. lime require $19 \times 1300 \times 0.21 =$ ..... | 5,187 " |
| 4. 416.12 kg. iron reduced from $Fe_3O_4$ require $1648 \times 416.12 =$ ..... | 685,765 " |
| 5. $5,975 \times 0.02$ kg. P to be reduced from $P_2O_5$ require $0.12 \times 5966 =$ ..... | 716 " |
| 6. 427 kg. pig iron require for melting $427 \times 46 =$ .. | 19,642 " |
| 7. $90 - 20.8 = 69.2$ kg. slag require for melting $69.2 \times 30 =$ ..... | 2,076 " |
| 8. 2.89 kg. S changed into CaS require $2.89 \times 1093 =$ | 3,159 " |
| | 920,321 cals. |

### 2. Heat Brought in.

| | |
|---|---|
| 1,000 kg. Basic Bessemer metal cooled from 1650° to 1300° bring in $1000 \times 350 \times 0.2 =$ ..... | 70,000 cals. |
| Burning 3.76 kg. S to $SO_2 =$ ..... | 8,347 " |
| 183.5 kg. coke breeze = 160.53 kg. C. For carburizing the pig iron 26.40 + 10.88 = 37.28 required. The remainder, 123.25 kg. burned to CO bring in $123.25 \times 2473 =$ ..... | 304,797 " |
| 1030 kw. hrs. used in the test $1030 \times 864.5 =$ ..... | 890,435 " |
| Heat brought in = ..... | 1,273,579 cals. |

Therefore the efficiency of the furnace equals

$$\frac{920321 \times 100}{1273579} = 72\%.$$

In determining the energy necessary to produce 1 metric ton pig iron it must be remembered that the basic Bessemer metal charged at 1650° brings in $\frac{70000}{865.4} = 81$ kw. hrs., for the finished material was tapped at 1300° C. Therefore $1030 + 81 = 1111$ kw. hrs. were required to produce 427 kg. electric pig iron, which equals for the metric ton $\frac{1111}{427} = 2602$ kw. hrs.

The following important points were established by means of the test.

(1) The efficiency of the furnace is good, as was to be expected. It may be still further increased if the mixture for reduction were charged by machinery and not by hand, so that the frequent

opening of the working doors and the unavoidable heat losses could be avoided.

(2) The reduction of the ore takes place satisfactorily even with the use of dense fuel, chemically inactive, such as coke breeze with a high content of ash. The amount of reduction material necessary closely approaches the theoretical, due to the reducing atmosphere of the electric furnace.

(3) The phosphorus in the charge goes entirely into the iron.

(4) The sulphur in the charge is lowered more than half, due to the reactions between the oxides and sulphides of iron, so that lime additions to unite with the sulphur are probably unnecessary.

**Test 2.**—In order to increase the efficiency of the furnace efforts were made to lower the radiation from the upper surface of the bath by causing the charge to project still deeper into the iron bath in the hearth. A suitable way appeared to be the smelting of the charge in the form of briquettes. The briquettes were made of the same mixture as used in Test No. 1 plus 8% of steel-works tar. The whole was ground in a Chili mill, and pressed in an ordinary dolomite press. The briquettes were burned a little before being used. An interesting point is that these partially burned briquettes showed 0.35% reduced metallic iron.

A lowering in the power consumption with the use of these briquettes could not be proved, nor any increased smelting efficiency of the furnace compared with Test No. 1. The pig iron produced had a low sulphur content, and the chemical balance showed that a greater part had been gasified as $SO_2$. The same amount of ore was smelted as in Test No. 1.

**Test 3.**—As both tests showed that over half the total sulphur was gasified, and the iron was sufficiently low in sulphur, further tests were made on a mixture of ore and fuel without special lime additions. It was thought that because of the smaller slag volume, the power consumption would be lower, and that at the same time the iron would be sufficiently low in sulphur.

After Test 2 had shown the lack of efficiency of briquetting, the ore was used fine as it was taken from concentrating, and the coke breeze of the usual size. The results of the test were good.

A low sulphur white iron was produced, and somewhat fewer kw. hrs. per metric ton were necessary than with Test 1, and the furnace efficiency was somewhat higher; that is, the smelting time was somewhat shorter than with Tests 1 and 2.

**Test 4.**—This test was to show whether an addition of granulated iron to the mixture would shorten the time of melting, and give a saving in the energy consumed. It was really a carrying out of the so-called Lash process, which consists of using a mixture of ore, carbon, and slag-producing material with finely divided pig iron, the charge being kept loose and porous with sawdust. The reduction of the ore is helped by the carbide present in the pig iron. An example of a Lash mixture is as follows:

| | |
|---|---|
| Iron ore | 54% |
| Cast-iron turnings or granulated cast-iron | 27 |
| Sawdust | 4 |
| Limestone | 4 |
| Tar | 3 |
| Coke | 8 |
| | 100% |

From what has been said before, it is to be expected that ore reduction by the Lash process would give no advantage, for in the induction furnace there is present a permanent bath of metal, and therefore with the ordinary ore mixture the known good reactions in the Lash process must take place anyway. In melting a metric ton of pig iron by the Lash process, the power consumption will be rather bad because the iron enclosed in the charge has to be melted electrically.

The reduction mixture was charged in exactly the same way as described by Lash. The result of the test, however, gave neither a shorter melting time nor a lower power consumption per metric ton of pig iron from ore.

## CRITICISM OF IRON ORE SMELTING IN THE ELECTRIC HEARTH FURNACE

The smelting of iron ore in the electric hearth furnace, which is so simple experimentally, depends on two important factors before it can be carried out commercially. One of them is the power consumption, the other the durability of the furnace lining, that is, the costs for repairs per metric ton of iron produced.

The durability of the lining requires that the highest temperatures, such as those of the arc, must be avoided because the drop in temperature is too great for it to be taken up by the charge.

This question of smelting ore in the electric hearth furnace is therefore only to be solved by a type of furnace that does not work continuously at the highest temperatures, and with which the excess heat which attacks the lining can be carried off. In this case the lining costs will be very small, but a somewhat higher power consumption must be counted on.

From the discussion above the only furnace of this type at present is the induction furnace, and the tests show that on the one hand the furnace lining allows continuous operation, and on the other that the power consumption is within such limits that, under certain conditions, successful competition with the blast furnace is permissible. Such conditions are first, that there are no special requirements in regard to the physical properties of the ore and fuel. Even very fine raw materials can be smelted, but the best are of small grain size.

This factor becomes more important from day to day, for conditions continually press towards the mining of poorer grade ores and magnetic concentration, so that high percentage concentrates, small in size, are coming on the market. If these concentrates are to be smelted in the blast furnace, they must be first agglomerated or briquetted, a process that even without a binding agent, that is, using high pressure alone, or say sintering, is an additional expense, for in this case a preroasting cannot be avoided.

Also in smelting ore in the electric hearth furnace a small

sized material can be used for reduction with at least equal success to one of moderate size, which means that small waste fuel of any kind is available that up to now has been valueless. Even these two points are so important that under certain conditions they will allow the electric hearth furnace to work more economically than the blast furnace. Also in regard to the purity of the ores, especially the sulphur, the electric hearth furnace has great possibilities because of the considerable volatilization that takes place. High sulphur materials can be smelted, therefore, with acid slags and without the lime additions that are absolutely necessary in the blast furnace. Only so much basic flux need be charged as is necessary to give a liquid slag.

The concentration of the ores will therefore not have to be carried so far, especially when ores with an acid and basic gangue are to be used at the same time, for by suitable mixing a self-fluxing charge can be obtained. This allows the conclusion to be drawn, that under certain conditions the poorer iron ores can be smelted in the electric hearth furnace without previous preparation, especially if the gangue forms a flux, so that the iron output of the charge is not lowered by the addition of fluxes.

A further important advantage of smelting ore in the electric hearth furnace is that the harder steels can be produced direct. It is not favorable to immediately make a soft steel, for the iron bath is first carburized by the reducing material, so that at the end of the heat ore alone must be added in order to remove this carbon.

In the next section of the book it is explained how this process is comparatively expensive. Still steel with about 1.5 to 1.8% carbon can be produced direct, and if high in sulphur can be desulphurized at little cost; while, at the same time, if high in phosphorus it can be dephosphorized without removing the carbon, both by means of processes given in more detail in the next chapter.

The carbon consumption in the electric hearth furnace is as good as possible when the carbon is only burned to carbon-monoxide. Troubles that are always more or less unavoidable in

the blast furnace disappear altogether, as also the production of the valueless "transition iron," when the furnace is changed from one kind of iron to another. Add to this the simpler operation, the avoidance of water cooling, the possibility of regulating at will the temperature of the metal tapped, and no electrode consumption, are some of the results. All these are points that, under certain conditions, allow the electric hearth furnace to successfully compete with the shaft furnace for smelting ore.

### THE SMELTING OF IRON ORES IN THE ELECTRIC SHAFT FURNACE

The experiments made in the electric hearth furnace make one desirous of studying more economical methods of smelting. The disadvantages of the electric hearth furnace are briefly:

1. Low melting efficiency of the furnace during operation.
2. Large power consumption per ton of iron produced.
3. Frequently too high a consumption of reducing material.

The reason for the low furnace efficiency is that the mixture for reduction is charged cold so that it has to be heated electrically to the necessary temperature. As the radiation loss increases with the smelting time per ton, it follows that a shortening of the smelting time would give a better efficiency, and this requires the charging of heated material. This preheating must naturally be brought about without increased consumption of electric or other energy if possible, and the hot waste reduction gases are available without extra cost. They are most suitably used by charging the mixture high in the furnace so that the gases have to pass through it, giving up their heat. This necessitates arranging a shaft on the hearth furnace.

The carbon-monoxide produced in the hearth would not only have a thermal effect but also a chemical one, that is, the ore would be partly reduced, so that the furnace then has only to melt the iron in the mixture of iron and ore. In other words only the remainder of the iron ore has to be reduced, and the furnace is released from some of its work.

If the reduction gases are used only to preheat the charge, then the following rough calculation gives the advantage obtained: 533 cu. m. (1880 cu. ft.) of gases are produced per metric ton of iron, and the same may be used for preheating the charge and be cooled down to 200° C. There will be obtained therefore: $533 \times 1100 \times 0.24 = 140712$ cals., corresponding to $\frac{140712}{864.5} = 162.8$ kw. hrs. In producing a pig iron with 3% carbon there would be a saving in energy of $\frac{162800}{16055} = 10.14\%$, which means that the metric ton of pig iron will be smelted with $1605.5 - 162.8 = 1422.7$ kw. hrs.

On the other hand if the waste gases are used only for preliminary reduction of the ore, then the following rough calculations are obtained for the limiting case that the CO is all changed to $CO_2$. According to the equation $Fe_3O_4 + 2\,C = Fe_3 + 2\,CO_2$ the metric ton of iron would only require 143 kg. of carbon for reduction. Also, according to the equations:

$$Fe_3O_4 + 4\,C = 3\,Fe + 4\,CO$$
$$Fe_3O_4 + 4\,CO = 3\,Fe + 4\,CO_2$$

$$\text{only } \frac{94100 + 45000}{2} = 493000 \text{ cals.}$$

would be necessary. The total carbon required for the production of a 3% carbon pig iron will be $143 + 30 = 173$ kg. for 1030 kg. metal, and the following heat balance is obtained for this most favorable case.

| | |
|---|---|
| 1383 kg. ore heated to 1300° C. = 1381 × 0.2 × 1300 | = 359,060 cals. |
| 173 kg. C. heated to 1300° C. = 173 × 0.2 × 1300 | = 44,980 " |
| 1000 kg. iron heated to reducing temperature | = 493,000 " |
| 1000 kg. iron heated to melting temperature | = 47,880 " |
| | 944,920 cals. |

This corresponds to $\frac{944920}{864.5} = 1093$ kw. hrs. per 1030 kg. pig iron, or 1061 kw. hrs. per metric ton. It is here assumed that

the $CO_2$ leaves the furnace at 1300° C., and if the excess heat of the $CO_2$ were further used to preheat the charge, and the gas allowed to escape at 200° C., then the power required would be lowered as follows:

From the equation $Fe_3O_4 + 2\,C = Fe_3 + 2\,CO_2$
168 kg. Fe produce $2 \times 22.4 = 44.8$ cu. m. $CO_2$, or 268 cu. m. per metric ton of iron. If the heat from 1300° to 200° is used for preheating then there is obtained $268 \times 0.24 \times 1100 = 70752$ cals., corresponding to $\frac{70752}{864.5} = 81.8$ kw. hrs. In this case, therefore, $1061 - 81.8 = 979.2$ kw. hrs. are necessary to produce 1 metric ton of pig iron.

From this it may be seen that the use of the furnace gases for reducing the ore brings about a considerable lowering in the power required, just as well as their use for preheating alone. By utilizing these gases as much as possible, the electric furnace is relieved a great deal and the smelting time is considerably shortened. The idea of using the reduction gases is therefore justified particularly as, at the same time, there is obtained a desirable and much lower consumption of reducing material.

As is well known, however, carbon-monoxide can only be used up to a certain limited amount for the reduction of ore because the mixture of CO and $CO_2$ produced has no more reducing influence when a certain percentage of $CO_2$ is present. In the electric shaft furnace, therefore, one has to figure on a waste gas that consists largely of CO, and it is apparent that the carbon necessary for reduction will increase with increasing percentage of CO in the waste gases.

In smelting magnetite the carbon necessary per metric ton of pig iron with 3% carbon, when the percentage by volume of $CO_2$ in the waste gases is known, is calculated by the formula

$$\frac{286\,(100 - 3) + 30}{100 + CO_2\%}$$

In this way the following table has been prepared:

| Per cent. $CO_2$ in waste gases | Kg. carbon required per metric ton pig iron of 3% C. |
|---|---|
| 100 | 138 |
| 90 | 146 |
| 80 | 154 |
| 70 | 163 |
| 60 | 173 |
| 50 | 184 |
| 40 | 198 |
| 30 | 213 |
| 20 | 231 |
| 10 | 252 |
| 0 | 277 |

The principle of an addition of a shaft is naturally possible with any electric hearth furnace that has a fairly large hearth, and is the easiest in the case of the arc furnaces, for these always have a comparatively large hearth. The Stassano furnace forms an exception, for here the charge is heated by radiation alone and only the heat below the arc is used. Also the induction furnace can be built so that it is easy to add a shaft, and further as the depth of bath in the induction furnace can be fixed at any desired amount a shaft about 3 m. (10 ft.) high or over is permissible, which is completely sufficient because of the small amount of reduction gases produced and their slow passage through the shaft.

In principle, reduction with gaseous fuel is always preferable to solid fuel, for the latter only reduces the outer layers of the ore. Because of this the use of a gaseous reducing agent should shorten the time of operation and increase the efficiency of the furnace, for the reasons already given. At first it was feared that, with the use of a shaft, the heat would be immediately carried upward from the metal bath and the operation of the furnace thereby made more difficult. These fears, however, were shown to be groundless because preheating helped the furnace so that the same condition was obtained as before, but in a shorter time. It will be shown that the carrying away of heat from the hearth to the shaft only takes place slowly, and that in arc furnaces the heat must be artificially removed from the lower part of the furnace.

In addition to the economic advantages of the electric shaft furnace compared with the hearth furnace, the disadvantages should not be overlooked. They are:

1. No very fine material can be smelted, but only pieces that are not too large, nor on the other hand ore smaller than a hazelnut.

2. In smelting there is no removal of sulphur, therefore with ores, etc., rich in sulphur there must be added the necessary amount of fluxes to slag off the sulphur.

3. The slag must be tapped as a thin liquid, so that for this reason fluxes also must be added, which decreases the output from the charge. Therefore at present only high percentage ores can be used.

4. Only iron with considerable carbon can be produced, not the high carbon steels, and the subsequent refining of the iron is expensive.

5. The electrodes must be burdened only up to a certain amount per sq. cm. of section, so that with coke alone the voltage must be lowered, and with it the furnace efficiency.

The first important experiments with an electric shaft furnace were carried out by Héroult.

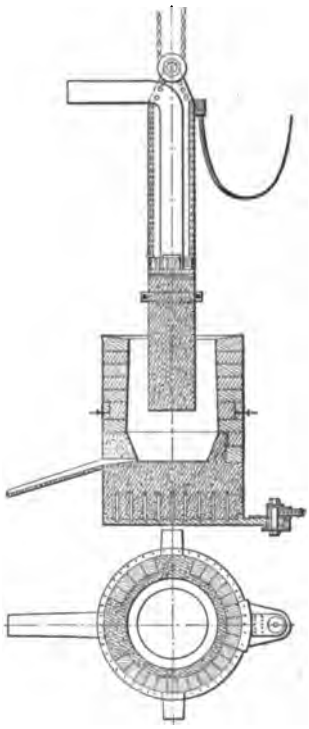


FIG. 123

### SMELTING TESTS IN THE SPECIAL HEROULT FURNACE

These very extensive experiments were carried out at the request of the Canadian Government in 1906 at Sault St. Marie, Ontario, in a furnace built by Héroult. As the accompanying illustration shows, Fig. 123, the

furnace differs very much from the Héroult steel furnace, and approaches the Girod in principle. The lower part is formed of carbon material stamped into place and constitutes one electrode, while the other, 1.8 m. (72 inches) long, reaches into the shaft from above and can be raised and lowered. The shaft is 1115 mm. (3′–10″) high. It is slightly conical and is built of fire-brick. The current was delivered to the furnace at 50 volts pressure.

Below are given details of these tests which are of the greatest interest because the electrode and furnace lining stood up for at least several days.

**Test No. 13.**—The raw materials had the following composition:

*Wilbur Magnetite,*

| | | |
|---|---|---|
| $SiO_2$ | = 6.20% | |
| $Fe_2O_3$ | = 55.42 | Fe = 56.69% |
| FeO | = 23.04 | |
| $Al_2O_3$ | = 2.56% | |
| CaO | = 2.00% | |
| MgO | = 6.84% | |
| MnO | = 0.258% | |
| $P_2O_5$ | = 0.023% | P = 0.01% |
| S | = 0.05% | |
| $CO_2$ | = 3.609% | |
| | 100.00% | |

*Charcoal,*

| | |
|---|---|
| Moisture | = 14.00% |
| Volatile matter | = 27.56% |
| Fixed carbon | = 55.90% |
| Ash | = 2.54% |
| S | = 0.058% |

*Sand,*

| | |
|---|---|
| $SiO_2$ | = 81.71% |
| $Fe_2O_3$ | = 0.09% |
| $Al_2O_3$ | = 14.27% |
| CaO | = 1.60% |
| MgO | = 1.11% |
| Alkali | = 1.22% |

The test lasted 61 hrs., 25 mins. The results were:

9573.23 kgs. ore smelted
2973.75 " charcoal smelted
540.23 " sand smelted
5832. " pig iron produced
462.67 " charcoal used per metric ton
1726 kw. hrs. used per metric ton

The analyses of the pig iron and slag were:

*Pig iron:*

| | |
|---|---|
| Si | =0.04 to 3.7% |
| S | =0.012 " 0.075% |
| P | =0.017 " 0.029% |
| Mn | =0.20 " 0.27% |
| Gr. C | =3.53 " 3.70% |
| Total C | =3.92 " 5.18% |

*Slag:*

| | |
|---|---|
| $SiO_2$ | =39.30% |
| $P_2O_5$ | =traces |
| MgO | =27.06% |
| FeO | = 1.21% |
| $Al_2O_3$ | =18.87% |
| CaO | =15.55% |
| MnO | = 0.35% |
| S | = 0.32% |

In regard to the charcoal used the theoretical amount necessary was determined as follows:

In 1 metric ton of ore there are:

| | |
|---|---|
| Fe as $Fe_2O_3$ = | 387.94 kgs. |
| Fe " FeO = | 179.21 " |
| Slag-forming constituents = | 176.00 " |

From this we may calculate the theoretical carbon required:

| | |
|---|---|
| 387.94 kgs. Fe reduced from $Fe_2O_3$ by C forming CO uses = | 124.52 kg. C |
| 179.21 kgs. FeO reduced by C forming CO use = | 38.35 kg. C |
| | 162.87 kg. C |
| 567.12 kgs. Fe as pig iron with 47% require = | 26.66 kg. C |
| | 189.53 kg. C |

This equals $\frac{189.53 \times 1000}{567.15} = 334.2$ kg. per metric ton.

The actual amount of charcoal used was 462.67 kg. containing $462.67 \times 0.559 = 258.64$ kg. carbon. It follows from this that $334.2 - 258.6 = 75.6$ kg. of the carbon necessary were either replaced by the volatile constituents of the charcoal, or else the CO produced reduced some of the ore in the shaft of the furnace. It is therefore clear that the thermal and chemical processes taking place in the shaft are of the same nature as those in the ordinary blast furnace, whereby the electric furnace is helped.

The small power consumption is very remarkable for it only slightly exceeds the theoretical, when the melting of the slag is taken into consideration. From this it is certain that the heat is mostly used in the interior of the furnace and that because of the heat stagnation near the arc the brickwork will be strongly attacked. The test unfortunately had to be discontinued because of the electrode not working properly.

**Test No. 14.**—(Time of test: 64 hrs., 30 mins.)

The results were:

| | |
|---|---|
| 4943.2 | kg. Blairton ore smelted |
| 2936.95 | kg. charcoal |
| 338.23 | kg. limestone |
| 88.71 | kg. sand |
| 5386.71 | kg. pig iron produced |
| 1968 | kw. hrs. used per metric ton |
| 545 | kg. charcoal |

**Analyses.**

(*a*) *The ore:*

| | | |
|---|---|---|
| $SiO_2$ | = 6.60% | |
| $Fe_2O_3$ | =60.74 | Fe=55.85% |
| FeO | =17.18 | |
| $Al_2O_3$ | = 1.48% | |
| CaO | = 2.84% | |
| MgO | = 5.50% | |
| Mn | = 0.13% | |
| $P_2O_5$ | = 0.037% | P=0.016% |
| S | = 0.57% | |
| $CO_2$ | = 4.923% | |

and loss on ignition.

(*b*) *Limestone:*

| | |
|---|---|
| $SiO_2$ | = 1.71% |
| $Fe_2O_3$ $Al_2O_3$ | = 0.81% |
| $CaCO_3$ | =92.85% CO=51.96% |
| $MgCO_3$ | = 4.40% MgO=2.09% |
| P | = 0.004% |
| S | = 0.052% |

(*c*) *Pig iron produced:*

| | |
|---|---|
| Si | = 3.05 to 5.15% |
| S | = 0.027 " 0.332 |
| P | = 0.024 " 0.037 |
| Mn | = 0.07 " 0.11 |
| Graph. car. | = 2.72 " 3.46 |
| Total car. | = 3.54 " 4.16 |

(*d*) *Slag:*

| | |
|---|---|
| $SiO_2$ | =33 to 37% |
| $Al_2O_3$ | = 9 " 18% |
| CaO | =18 " 30% |
| MgO | =21 " 30% |
| MnO | = 0.01 " 0.05% |
| FeO | = 0.4 " 0.9% |
| S | = 2 " 3% |

**Test No. 16.**—(Time of test: 38 hrs., 20 min.)

*The results were:*

| | |
|---|---|
| 2175.6 kgs. | Calabogie ore smelted |
| 1611.7 " | charcoal |
| 587.9 " | limestone |
| 34.1 " | quartz |
| 3246.0 " | pig iron produced |
| 497.0 " | charcoal used per metric ton |
| 1970 | kw. hrs. per metric ton |

**Analyses.**

(*a*) *Ore:*

| | |
|---|---|
| $SiO_2$ | = 6.06% |
| $Fe_2O_3$ | =58.00 } Fe=59.85% |
| FeO | =24.78 } |
| $Al_2O_3$ | = 1.00% |
| CaO | = 0.40% |
| MgO | = 6.00% |
| $P_2O_5$ | = 0.046% P=0.02% |
| S | = 0.17% |
| $CO_2$ | = 3.544% |

and loss on ignition.

(*b*) *Charcoal:*

| | |
|---|---|
| Moisture | = 2.20% |
| Volatile matter | =20.60% |
| Fixed carbon | =74.40% |
| Ash | = 2.80% |

(*c*) *Lime.*—The same limestone was used as in Test No. 14. No analysis was made of the quartz.

(*d*) *Pig iron produced:*

| | |
|---|---|
| Si | = 1.22 to 2.03% |
| S | = 0.006 " 0.008% |
| P | = 0.047 " 0.093% |
| Mn | = 0.07 " 0.12% |
| Graphitic C | = 3.87 " 4.55% |
| Total C | = 4.40 " 5.06% |

(*e*) *Slag produced:*

| | |
|---|---|
| $SiO_2$ | =30.88% |
| $Al_2O_3$ | = 9.67% |
| $P_2O_5$ | = 0.014% |
| CaO | =36.14% |
| MgO | =20.82% |
| MnO | = 0.14% |
| FeO | = 0.73% |
| S | = 1.23% |

## CRITICISM OF IRON ORE SMELTING IN THE HÉROULT ELECTRIC SHAFT FURNACE

The three tests given above show the following consumption of power for the production of one metric ton of pig iron:

| Kw. Hrs. | Charcoal kg. |
|---|---|
| 1,726 | 463 |
| 1,968 | 545 |
| 1,970 | 497 |
| Average 1,888 | 501 |

This power consumption is good, exactly as in all the former tests, because the charge forms a good heat-insulator. Still, this concentration of heat has proved a disadvantage, for with the great drop in temperature between the arc and the walls of the furnace the limited amount of charge surrounding the arc is not enough to absorb it, and the result is a rapid destruction of the lining and uneconomical operation. The ascending reduction gases

cannot lead away the excess heat near the arc through the charge to the throat, so that the lower part of the furnace is necessarily quickly destroyed by the "stagnant heat."

The intended prereduction of the ore is brought about, although only to a moderate degree, so that the carbon consumption is still high. The long electrode hanging in the furnace is shown to be a mistake because it is continuously exposed to mechanical wear, and is also chemically attacked by the surrounding ore mixture. Because of this delays in operation may be caused.

From all this it follows that the problem of electric ore smelting is not to be solved by the Héroult type of furnace, because electrode consumption, delays in operation, and the lining costs exclude economy. The quality of the metal produced, on the other hand, is good. Phosphorus and manganese are completely reduced, the slag can be kept low in iron, and the production of low sulphur pig iron of any desired silicon is possible. As a reducing agent lump charcoal and also peat coke can be used.

### THE SMELTING OF ORE IN THE GRÖNWALL, LINDBLAD & STALHANE ELECTRIC SHAFT FURNACE

Grönwall, Lindblad & Stalhane knew that the amount of reducing gases developed was not sufficient to carry the excess of heat present near the arcs from the lower part of the furnace to the shaft where it could be used economically for preheating the charge. They therefore increase the amount of gas by forcing into the lower part of the furnace, by means of a fan, part of the waste gases drawn from the throat. The amount is regulated so that the excessive heat, which would soon lead to the destruction of the lower part of the furnace, is driven into the shaft.

Because of the continuous operating troubles experienced with the long Héroult electrode, Grönwall, Lindblad & Stalhane used three electrodes introduced at the sides of the lower furnace in their early tests.

A general view of the furnace is shown in the accompanying

illustration, Fig. 124. In principle it is similar to an ordinary small blast furnace, the electrodes taking the place of the tuyères. The extensive smelting tests carried out with all kinds of ores allow a definite opinion to be formed as to the practical efficiency of this type of furnace, and show that there is no more difficulty in making iron with 4 per cent. carbon in the electric furnace than in the ordinary blast furnace.* Theoretically, the direct production of the harder steels is also possible, but experience has shown that such steels do not have the required temperature, and must be tapped while thickly fluid, which leads to troubles in operation.

In regard to construction the furnace has shown that the expected advantages are obtained. First with reference to avoiding the stagnant heat in the lower part of the furnace which would lead to rapid wearing away. In the first test furnaces, which were built either with none or a very small shaft, the reducing gases escaped at 70° C., but with the new construction the gases at the throat have a temperature of 200° C. to 250° C. (see Fig. 129), and the radiation loss of the shaft is also equalized by these hot gases.

From this it follows that the lower part of the furnace will stand up better during operation, but the efficiency of the furnace will not be so great, that is the power consumption necessary per ton of pig iron will be higher.

Second, in regard to preheating and preliminary reduction of the ore, while smelting the ore in the electric furnace, having no shaft, only pure carbon-monoxide is produced, the waste gases in the electric shaft furnace give the following analysis:

| *In 1909* | *In 1911* | | | | | |
|---|---|---|---|---|---|---|
| *a Charge of Red Hematite* $Fe_2O_3$ | *Charge of Hematite* | | | | | |
| $CO_2$ = 45% | $CO_2$ | CO | H | $CH_4$ | N | O |
| CO = 40 | 27.2 | 57.5 | 14.8 | 0.0 | 0.5 | 0.0 |
| $H_2$ = 15 | | | | | | |
| *b Charge of Magnetite,* $Fe_3O_4$ | *Charge of Magnetite, Mch. 16 & 30* | | | | | |
| $CO_2$ = 30% | $CO_2$ | CO | H | $CH_4$ | N | |
| | 12.6 | 71.9 | 13.0 | 1.7 | 0.8 | |
| | 19.2 | 59.7 | 17.6 | 2.5 | 1.0 | |

* See American Electro-Chemical Society, p. 400, 1911. Robertson.

According to the researches of Bauer and Glaessner, the reduction of iron ore by carbon-monoxide begins at about 650° C., and is most active at about 700° C.

On the other hand, according to the tests made at Trolhättan in 1911, and given by Robertson, the reduction of magnetite

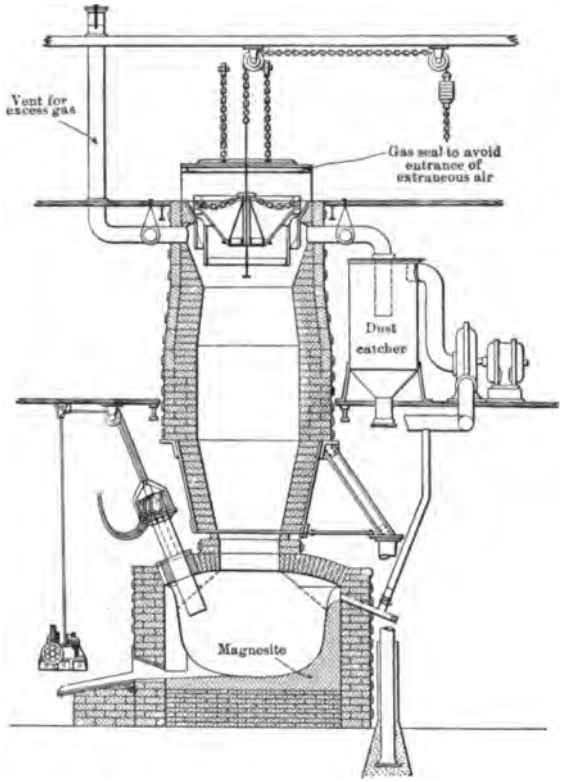



FIG. 124.

by carbon-monoxide takes place at as low a temperature as 300° C. As the above table shows, this furnace gas contains about 72% of that gas, so that reduction of the charge by the gas rich in CO probably takes place throughout the whole of the lower half of the shaft, since the temperatures from the official report of the Jernkontoret on the working of the Trolhättan furnace for the month of January, 1911, gives a tempera-

ture at the foot of the shaft (Point No. 1, in Fig. 125) at 534° C., and at point No. 4 at 351° C. The readings at point No. 5 were discontinued, but from the other figures given it would appear that the temperature at this point is not below 300° C.

As the gases in the electric shaft furnace leave the throat at 200° to 250° C., the chosen height of shaft of 5 metres (16′ 4.8″)

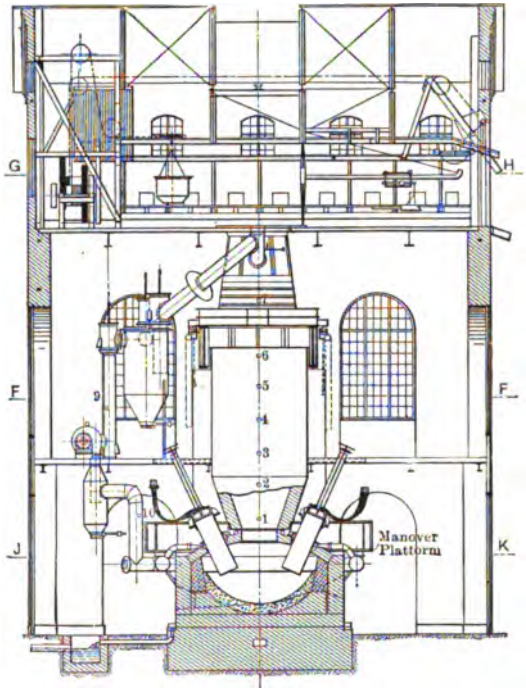



FIG. 125. The Grönwall, Lindblad and Stalhane furnace, design of 1911.

is more than sufficient. With the use of the Lange bell alone this height can be lowered, and with the use of the Parry cone at the same time, the effective height can be considerably decreased.

The high hydrogen content of the gas comes partly from the hydrogen contained in the reducing agents, but partly from the moisture in the charge, which is decomposed. Hydrogen does not have a special reducing action in the presence of carbon-monoxide, which explains the given high hydrogen content.

This is shown by recent experiments in the production of pure hydrogen in large amounts which consist of strongly heating iron ore in a muffle furnace, and treating it with water-gas. The ore is reduced, yet almost the whole of the hydrogen passes from the furnace unoxidized, and is used for heating the furnace. The reduced iron is then employed to produce pure hydrogen, by passing steam over it.

That an active prereduction takes place in the electric blast furnace is proved by the gas analyses, and the saving brought about in this way should be considered in calculating the amount of the reducing agents to be charged. This saving is based on the ratio of $CO_2$ to CO in the waste gases, which, for example, in the case of magnetite may be 40 $CO_2$ : 60 CO. The gas contains 100 carbon to 140 oxygen, the latter coming from the magnetite $Fe_3O_4$, the amount being $\frac{140}{4} = 35$. This is to say that the reduction process is based on the formula 35 $Fe_3O_4$ + 100 C. According to this $35 \times 3 \times 56$ parts of iron and $(100 \times 12) + 3$ parts of carbon should be charged for the production of a pig iron with 3% carbon. If the amount of $CO_2$ in the gases falls below 30%, then there is an excess of raw material over the carbon present for reduction, because more ore enters the lower part of the furnace, and some additional material rich in carbon must be charged. On the other hand, if the charge contains too much carbon, then the lowerp art of the furnace becomes filled up with it, and some additional lower carbon material must be charged.

In regard to the slag, a singulo-silicate is the best, with the formula $SiO_2$ 2 CaO, and the proper amount of lime to produce this must be added to the charge. As with the ordinary blast furnace so also here it is not profitable to run too basic a slag, as the power consumption increases more than it should.* In this case the slag also very often contains calcium carbide formed by the influence of the arc. The power consumption per ton

* The analyses of slag, according to Leffler, which follow show that these have generally been kept more silicious than desirable for the basic lining of the hearth. This, however, has been done for the purpose of obtaining

of pig iron naturally depends on the amount of slag that has to be melted, because it must be tapped in a fluid condition.

Technical knowledge in 1909 was such that only high percentage ores with 65 to 68% iron could be successfully smelted, which were as low as possible in sulphur, and which in no case gave more than 10% of slag.

Further progress was made in the 1910 and 1911 tests such that ores running as low as 53.25% iron and containing .055 sulphur (Nordmarken coarse washed ore) were successfully smelted.

Ores with high sulphur should therefore be roasted before smelting in order to reduce the amount of lime necessary to be added to the charge. This roasting is comparatively easy with ores with an acid gangue, an average result with Swedish magnetite showing:

| | | |
|---|---|---|
| Before roasting | 0.7 % | sulphur |
| After 24 hours | 0.3 % | " |
| " 48 " | 0.1 % | " |

With a large electric shaft furnace plant the waste gases can be used for heating the roasting furnaces. Certain magnetites swell during roasting, do not break up, but change into red hematite. This change probably only makes somewhat lighter the consumption of reducing material and electric energy, for in the ordinary blast furnace 100 parts of magnetite need 100 parts of coke, while the same amount of red hematite takes 90 parts of coke. Fortunately, definite figures on this point have been obtained for electric furnace work, and are as follows:

These are taken from the 1910 and 1911 Trolhättan tests. In those singled out for comparison ores of about the same iron content (65%) were chosen. The first test lasted 2096 con-

results as closely comparable as possible with the treatment of the same ores by the ordinary blast furnace process.

ANALYSES OF SLAG

| $SiO_2$ | $Al_2O_3$ | $TiO_2$ | FeO | MnO | CaO | MgO | CaS | $P_2O_5$ | Total |
|---|---|---|---|---|---|---|---|---|---|
| 41.60 | 6.85 | 2.72 | 1.49 | 1.48 | 28.91 | 16.70 | .063 | .00 | 99.813 |
| 46.82 | 5.06 | .. | 6.89 | 0.23 | 33.27 | 7.97 | .023 | .041 | 100.2 |

secutive hours and used 1,760,884 kg. (about 1,760 tons) of natural magnetite ore. The charcoal used per ton of iron equalled 415.7 kg. (914 lb.), containing 70.5% C. The second test lasted 193 hours and used 223,626 kg. (about 223 tons) of magnetite ore of which about 87% was roasted. The charcoal used per ton of iron here equalled 376.3 kg. (829 lb.), containing 73.5% C. The slightly higher carbon in the charcoal content of the latter case is perhaps offset by only 87% of the ore, in this case having been roasted, thus making the comparison with raw and all roasted ore better, and about as it would be if in the one case all the ore had been roasted and the charcoal in each case contained the same carbon content. The reduced amount of charcoal used for the roasted ore is about the same as with ordinary blast furnace practise, *viz.* 10%.

Ores with a basic gangue give great trouble in roasting, for the sulphur forms gypsum, and the intended reduction in sulphur is prevented, therefore such ores high in sulphur should not be used in the electric shaft furnace.

Fairly rigid requirements are also necessary in the physical properties of the ore to be smelted. The most suitable size is that of a large walnut, and only a little pure ore should be present. Lump ores have, therefore, to be crushed and none can be used which give a considerable percentage of fines on crushing. This is sometimes a great disadvantage because of the brittle character of many magnetites, etc. The reducing agent also ought to be about the size of one's fist, as much as possible, and fine material can only be used with difficulty and in small amount.

Formerly, *i.e.*, in the earlier tests only charcoal could be used, or a mixture of coke and charcoal. Since then, however, a 3000 to 3500 HP furnace of the Grönwall, Lindblad & Stalhane type has been completed and is in operation at Hardanger, Norway, where English Durham coke, carrying about .6% sulphur, is being used. This is according to Richards, A.E.C., Society, 1911, p. 417, and from private advices from D. A. Lyon.

In regard to the practical operation in 1909, small charges had to be used corresponding to the small size of the furnace,

that is to say, charges containing about 100 kg. (220 lbs.) of ore. In the larger furnace of 1911 the average charge over a 6 months' period was 425 kg. of ore (937 lbs). One-half of the ore should be thrown around the outside, and the rest with the reducing material and lime in the centre. If the charge were placed only in the centre, the 1909 furnace would easily hang, ordinarily due to the separation of carbon. Eighty charges containing 8 metric tons of ore were smelted in 24 hours, which with a 65% ore gives a total output of 5.3 to 5.4 metric tons of metal, obtained at intervals of 6 hours. Because of the small amount of slag, it was allowed to remain in the furnace. and was tapped together with the metal.

The results confirm those already obtained with the Héroult furnace, namely, that the smelting process is the same as that of the ordinary blast furnace, so that from a corresponding ore any desired pig iron can be obtained by running a suitable slag, and regulating the furnace temperature. With a high temperature the iron contains more carbon, and if at the same time a basic slag is run the manganese of the ore is completely reduced, and a low sulphur iron is obtained because of the complete removal of the sulphur in the slag. The silicon content when running a basic slag and high temperature decreases, and under these conditions a part of the phosphorus can remain unreduced in the slag. On the other hand if the slag is acid the manganese is partly slagged off, and with high temperatures a high silicon iron is obtained. Just the same conditions obtain here, therefore, as in the ordinary blast furnace. In operation it is always desirable to produce an iron as low in carbon as possible, which is the most favorable for foundry purposes, and also for subsequent refining into steel.

In regard to power consumption, in the tests ending in 1909, 280,307 kilograms of iron were produced in 1903.5 hours, during 5.9% of which no work was done due to troubles with the machinery. For each metric ton, 3181 kw. hrs. were used with an electrode consumption of 30 kg. or 66 lb. = (0.015%), and an electrode loss of 8 kg. or 176 lb. = (0.004%). The production from the ore was 63.5% and from the charge 60.02%.

The reducing agent weighed 354. kg. (779. lb.), and consisted of 41.7% coke and 58.3% charcoal, and a total of 35.41% was necessary, which corresponds to a consumption of 28% pure carbon. From this data the efficiency of the electric shaft

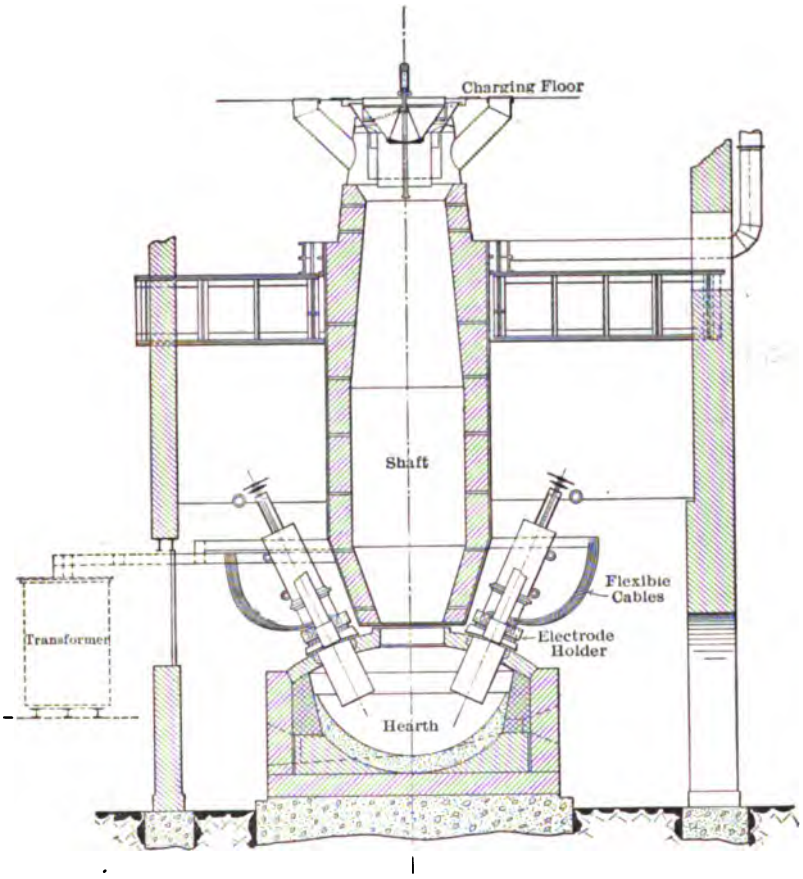



FIG. 126.—The Grönwall, Lindblad & Stalhane furnace. Latest design of 1912. Note lower position of electrode clamp.

furnace can be calculated. The pig iron may be taken as containing 1% silicon and 3% carbon, which leaves 96% iron, the ore as magnetite, and the waste gases as containing 30% $CO_2$ and 70% CO.

100 kg. of the waste gases contain 30 + 70 = 100 kg. carbon, and (2 × 30) + 70 = 130 kg. oxygen. In the reduction of magnetite 130/4 kg. $Fe_3O_4$ must be present to supply the oxygen,

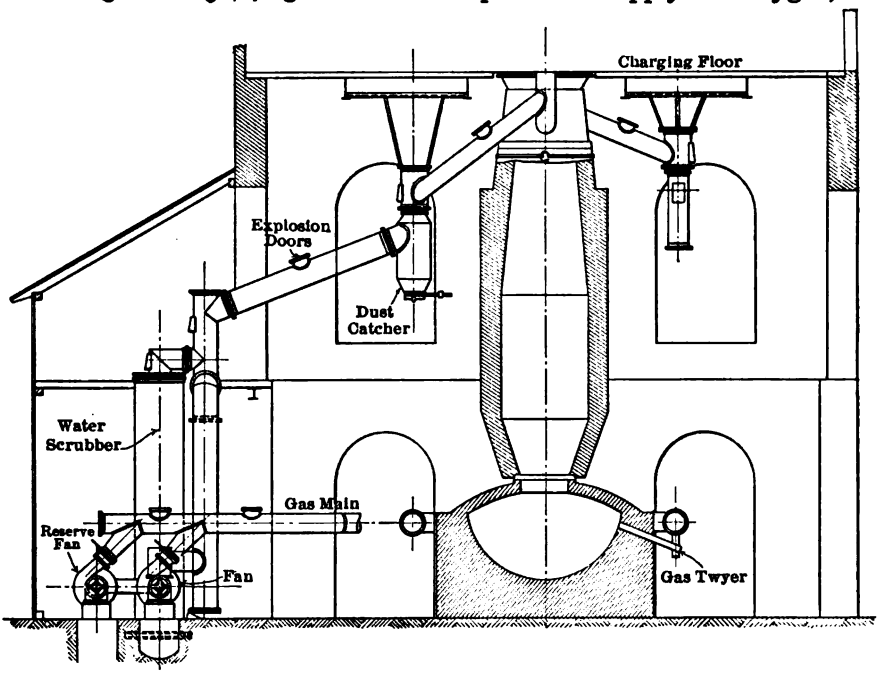



FIG. 127.—The Grönwall, Lindblad & Stalhane furnace. Gas circulation of 1911.

and 130/2 = 65 parts of silica to supply the silica. Reduction takes place according to the following formulæ:

1. $\frac{130}{4}$ kg. $Fe_3O_4$ + 100 kg. C = 30 $CO_2$ + 70 CO

or 13 kg. $Fe_3O_4$ + 40 kg. C = 12 $CO_2$ + 28 CO

2. 65 kg. $SiO_2$ + 100 kg. C = 30% $CO_2$ + 70% C.

This gives (12 × 12) + (28 × 12) = 480 kg. carbon, which according to the analysis of the gas gives (12 × 44) + (28 × 28) = 1312 kg. gas, that is to say, 1 kg. carbon gives $\frac{1312 \times 100}{480}$ = $\frac{41}{15}$ kg. gas. (1 lb. carbon gives 2.73 lb. gas.)

13 kg. of magnetite require 40 kg. carbon for reduction, so that for the smelting of $13 \times 3 \times 56 = 2184$ kg. iron $40 \times 12 =$ 480 kg. carbon are necessary, or for 960 kg. iron $\frac{960 \times 480}{2184} =$ 210.99 kg.

$65 \times 28 \times 364$ kg. silicon reduced from silica require $100 \times 12 = 240$ kg. carbon or 10 kg. silicon require 6.59 kg. carbon.

For carburizing the iron, 30 additional kg. of carbon are necessary, so that the total requirement of carbon necessary for the production of 1 metric ton of pig iron amounts to $210.99 + 6.59 + 30.00 = 247.58$ kg. (545.8 lb.).

From this there is formed $(210.99 + 6.59) \times 41.15 =$ 594.72 kg. waste gases (1311.1 lb.).

With an output from the charge of 60%, 960 kg. iron require a charge of $\frac{960 \times 100}{60} = 1600$ kg., with $\frac{960 \times 100}{72 \times 41} = 1325.71$ kg. $Fe_3O_4$. This will produce $1600 - 1325.71 = 274.29$ kg. slag from which $\frac{10 \times 60}{28} = 21.43$ kg. silica are reduced and enter the iron, leaving $274.29 - 21.43 = 252.86$ kg. (557.4 lb.).

*Heat requirements.*—The combustion of 1 kg. carbon producing the waste gas analysis given above creates $(0.3 \times 8080) + (0.7 \times 2470) = 4153$ cals.

| | |
|---|---|
| Reduction of 960 kg. iron from $Fe_3O_4 = 960 \times 1648 =$ | 1,582,080 cals. |
| Reduction of 10 kg. Si from $SiO_2$ $10 \times 7829 =$ | 78,290 " |
| Smelting and overheating of 1000 kgs. pig iron $= 1000 \times 280 =$ | 280,000 " |
| Smelting and overheating of 252.86 kgs. slag $252.86 \times 595 =$ | 150,452 " |
| Heating of 594.72 kgs. $CO_2$ and CO to 200° C. $594.72 \times 200 \times 0.245 =$ | 29,145 " |
| | 2,119,967 cals. |

*Heat Supplied:*

| | |
|---|---|
| Combustion of 217.53 kgs. carbon $= 217.53 \times 4153 =$ | 903,610 cals. |
| Leaving to be supplied by the electric current | 1,216,357 " |
| Total | 2,119,967 cals. |

The theoretical amount of power necessary for 1000 kg. of pig iron is $\frac{1,216,357}{864.5} = 1408$ kw. hrs.

As 3181 kw. hrs. are required daily per metric ton, the efficiency is $\frac{1408 \times 100}{3181} = 44\%$. This low efficiency obtained in the 1909 tests is for a small test furnace run with constant supervision. The remaining 56% is lost by radiation and cooling. In this respect measurements have shown that the water cooling of the three electrodes carried away about 120 kw. hrs. per hour. This gives a total loss of $1903.5 \times 120$ for the entire smelting test, which equals 228,420 kw. hrs. or $\frac{228,420}{228.703} = 815.7$ kw. hrs. per metric ton, which corresponds to $\frac{815.7 \times 100}{3181} = 25.6\%$ of the electric energy supplied. Through radiation alone $56 - 25.6 = 30.4\%$ of the energy is lost.

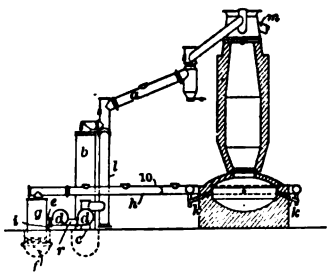


FIG. 128.—Modified gas circulation of 1912. Grönwall, Lindblad & Stalhane furnace.

It should now be considered whether and by how much the efficiency can be increased with a larger plant. Water cooling will still have to be used, and in this respect the efficiency can scarcely be increased. Apart from this the high water consumption, amounting to about ½ gallon per second (2 liters) is a disagreeable addition. On the other hand the radiation loss would be smaller because the cubic contents increase faster than the radiating surface of the furnace. Most important, however, is the fact that the smelting time per ton of iron will be lowered, and therefore the radiation per ton of metal will be considerably smaller with the increase in smelting efficiency.

Graphite electrodes will increase the smelting efficiency for they are better conductors than those of carbon, and although

they have a higher thermal loss (Chapter VI, Part I), yet this is more than equalized by the increased efficiency. At the furnace at Falun carbon electrodes were used, for there is no plant in Sweden making graphite electrodes. This dependence on electrode plants is necessarily very disadvantageous for all countries not having them. Experiments should be made to increase the life of the electrodes by mechanical means as much as possible, or the electrode consumption is proportionally high. It will not be much lower with a large furnace, as the electrodes are attacked because of their contact with the ore. Finally the consumption of reducing material is very much higher than it should be theoretically, which of course is also not desirable.

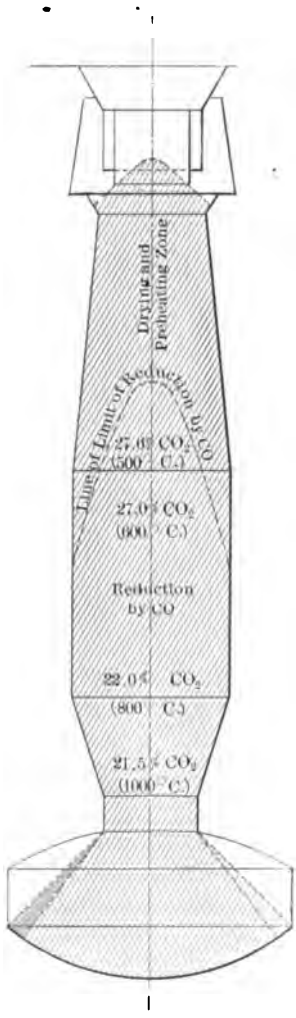

Drying and Preheating Zone
Line of Limit of Reduction by CO
27.0% $CO_2$ (500° C.)
27.0% $CO_2$ (900° C.)
Reduction by CO
22.0% $CO_2$ (800° C.)
21.5% $CO_2$ (1000° C.)

FIG. 129.—Temperatures in the Grönwall, Lindblad & Stalhane electric pig-iron furnace.

Below are given some details of recent test runs in larger furnaces, and it may be seen how these theoretical considerations have worked out in practise.

With regard to the run from Nov. 15, 1910, to April 9, 1911, in the newer Grönwall, Lindblad & Stalhane or Swedish Ludvika Elektrometal type furnace, 1882.496 kg. (about 1882 tons) of iron were produced in 3501.9 hours, during about 4.4% or 153.7 hours of which no work was done due to troubles with the apparatus. For each metric ton, 2391 kw. hrs. were used with an electrode consumption of 10.28

kg. (22.6 lbs.) gross, and 5.27 kg. (11.6 lbs.) net, per ton of iron produced. The per cent. of iron in the ore was 61.54% and the per cent. iron in the charge 57.00%. The reducing agent weighed 418 kg. (920 lbs.) per ton of iron produced and consisted of charcoal only, having a carbon content of 80.14%. The pig iron may again be taken as containing 1% silicon and 3% carbon, which leaves 96% iron. The average of the gases produced consisted of 23% $CO_2$, 60% CO, 10% H, 2% $CH_4$, and 5% N. From this data the efficiency of the electric pig-iron furnace may again be calculated as before, and in this case the efficiency is considerably higher, being about 59%.

After the furnace at Trollhättan was shut down from June to September, 1911, in order to make such changes as the operation of the furnace had demonstrated would be beneficial and such repairs as were necessary, the furnace was again put into commission. During the run from Sept. 3 to Sept. 30, 537.9 tons of pig iron were produced. For each metric ton of pig iron 1749 kw. hrs. were used with an electrode consumption of less than 10 kg. (22 lbs.) gross and 5 kg. (11 lbs.) net. The iron in the ore was 67.65% and the iron in the ore and lime was 65.02. The reducing agent weighed only 339.9 kg. now (748 lbs.), consisting of charcoal. With the same carbon content as before, 72%, this equals 245 kg. or 24.5% pure carbon. From this data the efficiency of the furnace can again be calculated and figured out to 80.5%. This corresponds to an output of over 5 tons of pig iron per kilowatt a year. The above efficiency corresponds favorably with the Swedish charcoal blast furnace of 82% and with 70% the usual coke blast furnace.

As a conclusion it may be said that the Grönwall, Lindblad & Stalhane electric shaft furnace is probably the first electric furnace in which ore has been smelted in some degree commercially. The weak point has been the furnace roof, which, in the 1909 furnace, either showed such small durability and therefore made continuous operation impossible, or else had to be cooled so strongly that the efficiency of the furnace suffered considerably. Further the close limits allowable in the chemical and physical composition of the charge, and the large electrode

consumption show that the furnace can be employed only under especially favorable operating conditions. The principle is first-rate, especially with regard to making the roof of the lower part of the furnace more durable, as far as possible without the use of water cooling, and so increasing the furnace efficiency. In this place the Lyon experiments conducted at Héroult, California, with the Noble furnace, should be mentioned. The following details are taken from a paper by Otto Frick, in *Metallurgical and Chemical Engineering*, December, 1911, on "The Electric Reduction of Iron Ores."

The Noble furnace is of the same type as that at Trollhättan, and like it in all essential points. This, however, is not the result of mutual understanding or communication. An illustration is given of the furnace at Héroult by Fig. 130. This furnace has now (1912) been rebuilt seven times. It has three single-phase transformers, each of 750 kilovolt amperes, connected to a three-phase system of 2200 volts and 60 cycles.

The low tension current is supplied to six graphite electrodes.

These electrodes enter into the charge as far as possible, and in this respect the practise differs from that at Trollhättan, where a space is left between the electrodes and the charge. The pressure of the charge on the electrodes is very nearly equal to their breaking strength, so that the additional force arising from a sudden descent of the charge easily causes their breaking at the conical screw joint. This strain can be reduced approximately 30% by lowering the inclination from 35° to 20°, and much improvement can be made in the joint.

No accurate figures are at hand as to the power consumption, but it has been stated by the manager of the plant that it has averaged 1940 kw. hrs. per ton.

With regard to gas circulation it has been found unnecessary to use any in the Noble furnace, where the electrodes penetrate the charge far enough to prevent arcing, so long as they remain unbroken.

The question of the smelting of ore in the electric shaft furnace can only be considered solved when the following requirements are met:

1. Water cooling lowered as much as possible.

2. The electrode consumption lowered, and the electrodes done away with as much as possible.

3. The radiation loss lowered by the smelting efficiency being raised as much as possible.

4. The waste gases composed of only pure carbon-dioxide,

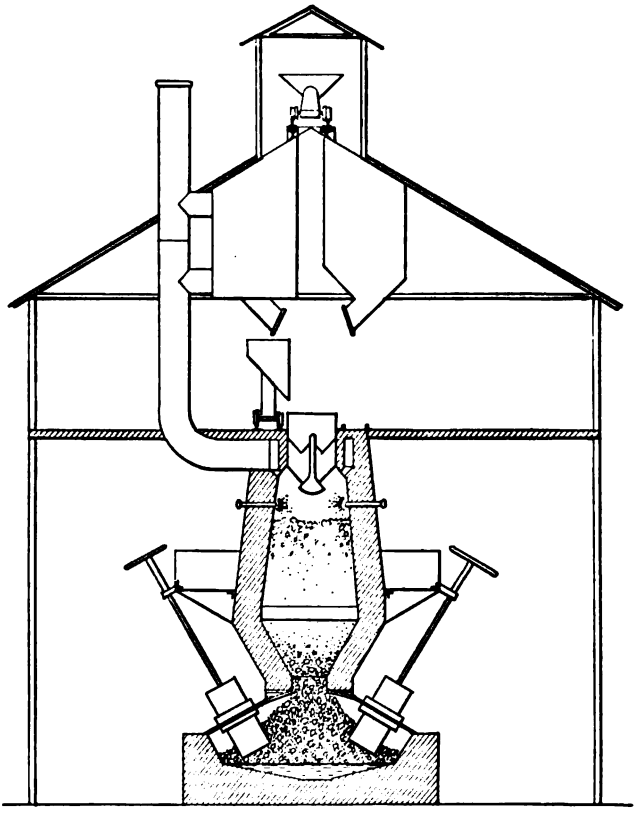


FIG. 130.—The Lyon furnace in California.

of suitable temperature, in order to lower the amounts of electricity and reducing material necessary.

Requirements 1 and 2 are very closely connected. So long as electrodes are used, cooling of the electrode heads cannot be

avoided, which brings about great heat loss, and necessitates a complicated furnace construction. Further great durability of the furnace lining is only possible if the high initial temperature of the arc is avoided, and the most suitable moderate temperature used. This requirement is only met by the induction furnace, for on the one hand electrodes are not used at all; and, on the other hand, as the experiments with the hearth induction furnace have shown the furnace lining is hardly attacked at all when smelting ore. An induction furnace with a wide hearth and a shaft built above is the one to claim the greatest interest for smelting ore, and so much the more that it can be operated at the highest temperatures if required. Any height of shaft can be chosen, so that the waste gases can be efficiently used for prereduction and preheating of the charge.

The radiation loss decreases with a larger furnace for the induction as for other furnaces.

In regard to the requirement that only pure carbon-dioxide, at a suitable temperature, should be given off, as waste gas, it is well known that carbon-monoxide loses the ability to reduce ore when a certain percentage of carbon-dioxide has been formed. It is therefore theoretically impossible to have a product of pure carbon-dioxide when charging ore and fuel.

The complete utilization of the waste gases is therefore only possible if they are burned afterwards, and used as much as possible for preheating the ore.

This preheating favors smelting only in that reduction is made more easy by an increase in the degree of oxidation, and also because the sulphur contents are lowered so that a low sulphur iron can be obtained without the addition of more flux to the charge. With finely divided ores the roasting also brings about a certain amount of agglomeration so that under these conditions fine ores, concentrates, etc., can be smelted in the electric shaft furnace. The heating and agglomeration of fine ores, if sufficient fluxing material is present, can be carried out in a revolving cylindrical furnace, the ore being charged wet just as it comes from magnetic separation for instance. Such agglomerating plants are already in satisfactory operation.

The use of coal dust firing which is recommended for the heating of these furnaces is unsuitable, as it gives rise to high fuel costs, and the ash of the coal makes the ore higher in slag-producing material so that it is more unsuitable for electric furnace work. It is, therefore, necessary to operate with waste gases, and an addition of producer gas should only be made when the difference in price between fine and lump ore is sufficiently great to bear the increased cost in fuel needed for the production of the producer gas.

Such an ore, however, greatly preheated, cannot be charged directly with the reducing material, as it is immediately reduced, forming carbon-monoxide, and so reduces the furnace efficiency.

The greatly heated ore must be charged alone, and the reducing material introduced in the hearth of the furnace at the deepest zone of the shaft. The physical condition of this reducing material is not important, if solid, the most suitable size is fine grained. Very small fuels and even valueless waste can be used with complete success.

Also fluid-reducing materials such as tar, petroleum, and oil residues of all kinds can be used. This is of special interest to those countries which at present must import coke or charcoal, because these liquid fuels due to their high heating value and low ash contents are brought in at much more favorable freight rates. Finally gaseous reducing agents of all kinds can be used, such as producer gas. The carbon-dioxide should be as low as possible, and if fuels with much moisture are used, such as turf, brown coal, etc.,the gas should be cooled as thoroughly as possible to remove the moisture The troublesome precipitation of tar experienced in the cooling of producer gas is no disadvantage to the electric furnace, as opposed to other furnaces, for the tar can be collected, dried in centrifugal machines and used in the furnace as a reducing agent.

The carbon-monoxide or the solid liquid or gaseous materials used easily reduce the highly heated charge, and give warm waste gases rich in carbon-monoxide, which can serve to preheat more ore charges if air is added to combine with the combustible constituents.

In this way it is possible to considerably reduce the consumption of reducing material, and to come very near the theoretical minimum; which, in the case of magnetite and the production of a pig iron with 3% carbon, is 143 + 30 = 173 kg. of carbon (381.4 lbs.) per metric ton. The best figures reached so far as already mentioned are 245 kg. of pure carbon when making a pig iron with 3.64% C.

After nearly a year of further experience (215 days) in operating the furnace at Trollhättan, *Leffler* and Nyström contributed a supplementary report of 98 pages, to the meeting of the Jernkontoret at Stockholm, on May 31, 1912. It is not possible to do this report justice here by any abstract of it, still it may be instructive to mention some of the improvements recently made. The new gas circulation system was altered to better dry the gas returned to the furnace. Fig. 128 shows the latest design and is but little different from its predecessor shown by Fig. 127. The cooler acts on the condenser system and requires 100 liters of water per minute to reduce the temperature of the gas so that its moisture content is reduced from 4 grams per cubic meter to .5 gram.

Both high and low grade ores were used in this run, so that the furnace output dropped to about 15 tons daily from its normal capacity of 20 tons. This run again demonstrated that economical operations need a rich ore.

Fig. 129, which is reproduced from the July, 1912, *Metallurgical and Chemical Engineering*, shows the temperature and reaction in the furnace shaft. This abstract goes on to say:

The temperatures of iron and slag issuing from the furnace varied as follows:

| | |
|---|---|
| Iron | 1230° to 1420° C. |
| Slag | 1290° to 1460° C. |

A large table gives the temperatures taken at 8 points in the shaft, just inside the wall and in the middle; also the percentages of $CO_2$ in the gases at these different points.

There are various not very important irregularities in the figures, but the general average shows temperatures up to 985° in the middle at the lower part of the shaft and 585° half way

up; while near the wall it is 420° to 565° at the lowest hole and down to 15° at the highest.

The measured percentage of $CO_2$ shows that reduction takes place ordinarily only one-quarter way up the shaft at the sides and a little over one-half way up in the centre.

The extent of the zone of reduction by CO is clearly shown in Fig. 129, in which also some temperatures are indicated.

*Cooling Water.*—The contacts and jackets through which the electrodes worked were water cooled. The heat carried away thus varied from 172 to 288 kw., or 10.47 to 19.30 (average 14.50) per cent. of the power used.

*Thermal Balance.*—The heat balance per 1000 kg. of pig iron is worked out for the four weeks, Sept. 3 to Oct. 1, 1911, in which the average power used (high tension side) was 1407 kw., and the power consumption 1749 kw. hours per ton of pig iron; the ores worked were the rich Tuolluvaara ores. The heat balance is, per kg. of iron:

| | | |
|---|---|---|
| Combustion C to $CO_2$ | 567 | calories |
| Combustion C to CO | 381 | " |
| Electric energy | 1504 | " |
| | 2452 | calories |
| Consumed in reductions | 1620 | calories |
| Decomposition of limestone | 35 | " |
| Evaporation of water | 24 | " |
| Sensible heat in throat gases | 26 | " |
| Sensible heat in slag | 75 | " |
| Sensible heat in pig iron | 300 | " |
| Cooling water | 195 | " |
| Lost in transformers | 43 | " |
| Lost in conductors | 44 | " |
| Radiation and conduction | 90 | " |
| | 2452 | calories |

The authors then make some interesting calculations, the results of which are, in brief, as follows: The gas kept in circulation was 2.28 times the gas normally produced and escaping. Assuming this gas to enter the furnace at 22° and to enter the shaft at 1000°, it carried into the shaft as sensible heat 343,118

calories per ton of iron, or 22.9 per cent. of all the heat electrically generated in the crucible. Since it carried with it 22.5 kg. of water vapor and 174 kg. of $CO_2$, both of which are decomposed by the glowing carbon, the net heat absorbed in these decompositions is 160,283 calories, or 10.7 per cent. of the electric energy used. The gas circulation therefore transferred physically and chemically 33.6 per cent. = 1/3 of the electrical energy used from the crucible into the shaft of the furnace.

### THE USE OF THE ELECTRIC FURNACE FOR MELTING, FOR REFINING PIG IRON, AND FOR THE PRODUCTION OF ORDINARY AND SPECIAL QUALITY STEEL

Pig iron, that is the iron and carbon alloy, produced in the electric or ordinary blast furnace or in any way, contains other constituents such as silicon, manganese, sulphur, phosphorus, copper, arsenic, etc., which come from the charge. Some of these elements, such as copper and arsenic, are easily reduced from the ore and enter the metal, and cannot be removed economically by any metallurgical operation. The other elements, such as silicon, manganese, sulphur, and phosphorus, can be partly eliminated in the blast furnace and slagged off, and they can also be separated more or less from the finished metal by later metallurgical operations.

If the amount of one of these constituents is to be lowered in order to make the metal more suitable for any special purpose it is spoken of as a refining of the metal. Therefore a lowering in the carbon percentage of the metal is also to be considered as a refining. The refining process can be of various kinds, reducing and oxidizing, or consist of simple reactions such as:

$$FeS + Mn = MnS + Fe.$$

If an electric furnace is to be suitable for refining, then all processes, whether oxidizing or reducing, must be practicable; above all it must allow the carrying out of all metallurgical operations, such as are now used in the open hearth, converter, etc. The electric furnace, and this must be specially pointed

out, should not be different from an ordinary furnace, except that the heating is electro-thermal. The electric furnace, as such, except for the lining, should have no influence on the chemical composition of the bath of metal. Arc furnaces do not correspond altogether to these requirements, for an influence of the electrodes on the bath cannot be avoided even with careful operation.

Electric heating of the furnace has the great advantage that the influence of the hot gases on the charge, which is present in the furnaces used now, is excluded, so that work can be carried out with an oxidizing, neutral, or reducing atmosphere at will. Even the maintenance of a neutral or reducing atmosphere is not only very difficult with the present furnaces but really impossible, except with crucible and muffle furnaces.

The induction furnace completely meets these requirements, for in it a reducing or oxidizing atmosphere can be obtained as desired. With the arc furnace on the other hand, reduction processes take place very well, but oxidation processes only slowly, due to the reducing action of the electrodes, and with an increased use of oxidizing material there is more electrode consumption. Otto Thalner gives expression to this in his address before the "Oberschlesischen Bergwerksverein deutscher Chemiker," 1909, when he says: "The arc furnace is indeed a good reduction furnace, but a bad refining furnace." An electric furnace, however, to answer all requirements should allow reduction and oxidation processes to be carried out equally well, and this should be pointed out before anything is said about the metallurgy of iron and steel, the influence of impurities, or the refining of the metal.

**Phosphorus.**—This exists in the iron in the form of phosphide of iron which dissolves in the metal bath without difficulty up to 1.7% Phos., forming mixed crystals. Phosphorus segregates in both pig iron and steel, for the phosphide has the comparatively low melting point of 910° C. For instance, in gray foundry iron the well known separated bean-shaped pieces are sometimes found, which give the following analyses:

| | 1 | 2 | 3 |
|---|---|---|---|
| Bean-shaped pieces..... | 1.30% P | 1.30% P | 1.00% P |
| Solid piece near the beans.. | 0.60% P | 0.55% P | 0.50% P |

Analytical proof of its segregation in steel is given in the next section under Sulphur.

If a section is cut from a steel high in phosphorus, polished and etched with a solution of copper-ammonium-chloride, by Professor Heyn's method, the places rich in phosphorus will be colored dark, and one is in a position to determine the segregation in the material. As segregated material has considerably lower physical properties than normal material, a low phosphorus should be specified if a high quality is desired, so that if ordinary high phosphorus material is to be used for making high quality steel, it must be dephosphorized. In order to do this an American has proposed to destroy the phosphide by the addition of another element according to the equation:

Iron phosphide + metal = iron + metal phosphide.

Naturally a metal must be chosen that, in the form of phosphide, does not alloy with the iron but goes into the slag. Such reactions are theoretically possible, and have been carried out practically to a small extent. Even the silica holding desulphurizing slags of the electric furnace show a certain content of phosphides, which can be easily recognized by the garlic-like smell when the slags are moistened with water, but this method of dephosphorizing has not, so far, become of practical importance.

The removal of phosphorus is only possible with certainty, at present, when the phosphorus is oxidized to phosphoric acid, combined with lime, and removed as slag. The phosphorus is oxidized at low temperatures before the carbon, but at higher temperatures only after the removal of the carbon from the bath. One can therefore dephosphorize high carbon charges without having to previously completely remove the carbon. In this case the temperature of the bath should be kept low, an

easily fusible basic slag charged rich in oxide of iron, and at the end of the dephosphorization immediately tapped. To a certain degree this method of dephosphorizing requires considerable care and experience for complete success, although the melting of high carbon heats is economical.

Dephosphorization is more certain with low carbon and very high temperature, and at the same time strongly oxidizing and basic slags. Further, the oxidation of the phosphorus can be brought about as well by the oxygen in the ores as by that of the air. The maintaining of a basic slag naturally requires that the work be done on a basic hearth.

**Sulphur.**—Sulphur can exist in steel as MnS, as well as FeS. The latter can alloy with liquid iron while the former does not alloy with the liquid metal, and is therefore only present in the form of included material. If the bath of metal is allowed to stand long enough, then the MnS will rise to the surface because of its lower specific gravity, and can be drawn off. This is not possible with the remaining FeS which remains alloyed with the liquid metal. For this reason the slags which separate from the metal, for example from basic Bessemer iron, in casting ladles, or mixers contain a high percentage of sulphur and also manganese, present for the most part as MnS, while the amount of iron is not so great. This is shown by the following average analysis of ladle slag:

| | |
|---|---|
| Iron | 6% |
| Manganese | 42% |
| Sulphur | 10% |

If these slags come lower in sulphur, then oxidation of the sulphide of manganese by the air or by included oxide has taken place. A high manganese, however, is always a characteristic of these slags so that, after a preliminary roasting, they can be used in the blast furnace as an ore of manganese.

Sulphur is harmful to pig iron, steel, and wrought iron, the reason probably being the low freezing point of FeS, whereby during the cooling of the bath of metal it segregates to the centre, and also brings about the red short character of high sulphur material.

It is therefore necessary to desulphurize the iron as much as possible before it is made into steel, a process that is carried out by the addition of ferro-manganese to the liquid bath, if there is not enough manganese already present. The sulphide of iron is then, decomposed according to the equation:

$$FeS + Mn = MnS + Fe$$

and if sufficient time is given the MnS rises to the surface of the bath into the slag and can be removed. The process only takes place smoothly if a considerable excess of manganese is used. Even in this case, however, no total desulphurization is possible. The sulphur can only be lowered to a certain degree, about 0.05%, which is still considerably too high for special quality steel.

In liquid pig iron or steel, rich in manganese, that has stood long enough before pouring, the sulphur is to be thought of as being present exclusively in the form of FeS. If a microscopic section is taken from high sulphur material, polished and etched as described under "phosphorus," and the dark segregation places examined, then a considerably higher sulphur content is found than in the ground mass, but only the same manganese. If the segregation were a question of the separation of MnS then, with an increasing sulphur content, there would also be noticed an increase in manganese, which is not the case.

Below are given some analyses:

| | Mn% | S% | P% |
|---|---|---|---|
| *First material:* | | | |
| Pure ground mass..... | 0.48 | 0.067 | 0.050 |
| Segregate..... | 0.48 | 0.182 | 0.100 |
| *Second material:* | | | |
| 1. Very black segregate. | 0.30 | 0.097 | 0.155 |
| 2. Gray segregate..... | 0.30 | 0.055 | 0.079 |
| 3. Pure material..... | 0.30 | 0.040 | 0.047 |

The elongated sulphide inclusions often seen under the microscope that are usually assumed to be MnS are perhaps nothing more than inclusions of sulphur holding slag, which during the rolling of the hot ingot were not yet solidified in its

interior and therefore were rolled out. Also the general appearance of red short material during forging and rolling inclines one strongly to the opinion that the Fe−FeS alloy separates between the crystals but not inside the crystals themselves.

As already mentioned liquid steel produced in the ordinary way and therefore fairly high in sulphur must be further desulphurized for the production of good quality steel. For this purpose the electric furnace is suitable. The following two processes are those mostly used for desulphurizing in the electric furnace, and both take place most energetically at high temperatures. They also both require the use of a neutral or reducing atmosphere in the furnace and the melting of a strongly basic slag.

In order to make these basic slags easily fusible additions of fluor-spar, and quartz in the form of sand, are made.

(1) The use of the chemical reaction $FeS + CaO + C = Fe + CaS + CO$.

For carrying out this reaction, therefore, the help of carbon is necessary, and the process can be operated very satisfactorily in the arc furnace, due to the favorable influence of the electrodes. Carbon must be added to the bath, and for this reason the process is used only when it is a question of the production of high carbon steels. In melting very soft steels, one must either take into account a certain carbonization of the bath and later remove the carbon, or else be satisfied with a less complete desulphurization. Even if the carbon is only thrown on the slag covering from time to time, a certain absorption of carbon by the bath cannot be avoided.

(2) The use of the chemical reaction between silicon and sulphur whereby SiS is produced which escapes as gas.

$$FeS + Si = Fe + SiS.$$

If at the same time a lime carrying slag is formed on the metal bath a further desulphurization takes place according to the equation:

$$2\,FeS + 2\,CaO + Si = 2\,Fe + 2\,CaS + SiO_2.$$

The CaS is removed as slag. It is interesting to know that

both reactions take place almost quantitatively so that scarcely more than the theoretical amount of ferro-silicon must be added to the bath, and if desired a low silicon steel can be produced. The process is often used in the induction furnace and has the advantage that it can be used equally well for high and very low carbon heats. The reaction gives a very fluid slag because of the increase in the amount of silica.

Moreover, fluor-spar is also an equally good desulphurizing agent when ferro-silicon is used, according to the equation:

$$2\,FeS + 2\,CaF_2 + Si = Fe + 2\,CaS + SiF_4.$$

Further, in regard to desulphurization by means of silicon in the electric furnace a great many theoretical reactions have been suggested, a small selection from which is given below.

(*a*) With the use of burned lime.

1. $2\,CaO + SiS = CaS + SiO_2 + Ca -$, but there would result

$$Ca + Fe\,S = CaS + Fe.$$

2. $2\,CaO + 2\,SiS = 2\,CaS + SiO_2 + Si -$, but there would result

$$Si + FeS = SiS + Fe.$$

3. $2\,CaO + FeS + SiS = 2\,CaS + SiO_2 + Fe.$

The SiS in all these equations is thought of as being produced by

$$Si + FeS = SiS + Fe.$$

Also they all represent the same reaction, namely:

$$2\,CaO + 2\,FeS + Si = 2\,CaS + SiO_2 + 2\,Fe.$$

The slag will be made thinly liquid by the silica produced and, in this reaction, 1 sulphur requires ½ silicon.

(*b*) With the use of fluor-spar,

1. $2\,CaF_2 + SiS + FeS = 2\,CaS + SiF_4 + Fe.$

The SiS is produced by the equation $FeS + Si = Fe + SiS$.

2. $2\,CaF_2 + 2\,SiS = 2\,CaS + SiF_4 + Si.$

The Si would decompose more FeS.

Both reactions therefore mean the same, namely:

$2\ CaF_2 + 2\ FeS + Si = 2\ CaS + SiF_4 + 2\ Fe.$

The slag will become more basic, that is thicker, and by this reaction also 1 sulphur requires ½ silicon.

Résumé of the equations.

(*a*) $2\ CaO + 2\ FeS + Si = 2\ CaS + SiO_2 + 2\ Fe.$

(*b*) $2\ CaF_2 + 2\ FeS + Si = 2\ CaS + SiF_4 + 2\ Fe.$

The reactions are the same except that in one the oxide, in the other the fluoride, is the reagent; and by both processes the same amount of silicon is necessary.

Desulphurization by the alternate reaction between FeO and FeS and the formation of $SO_2$ cannot be carried out with fluid metal to complete success, and for this reason it is only suitable for such cases where complete desulphurizaion is not necessary.

**Silicon.**—The good influence of a certain silicon content in gray pig iron and gray iron castings is well known. To a certain degree too high silicon in the pig iron is a disadvantage for gray iron castings, particularly for the larger ones, as it brings about a coarsely crystalline structure, and therefore makes weaker castings. On the other hand the silicon in iron or steel can easily be raised by the addition of ferro-silicon to the molten bath.

Silicon can be removed from molten iron and steel by oxidation, as well by means of ore as by the oxygen of the air, a process that naturally takes place more easily on a basic than on an acid hearth. The silicon burns before the carbon if the temperature is low, at higher temperatures it is only removed completely when the carbon is already partly oxidized, while at high temperatures the silica in the slag is again reduced by the carbon in the bath.

**Copper and Arsenic.**—Neither of these elements can be removed economically at present from the bath, so that if a certain copper and arsenic content is required in the finished material, an appropriate mixture must be charged.

**Carbon.**—The carbon can be removed from the bath by the

oxygen of the ore or by that of the air, with the formation of carbon-monoxide. If the refining is carried out by means of ore, then iron is reduced, a process that requires heat. It is probable that the metal may dissolve a certain amount of carbon-monoxide, for iron heated in a stream of nitrogen shows a melting point of 1506° C., but when heated in a stream of carbon-monoxide only 1406° C., a phenomenon that is explained by the assumption that carbon-monoxide alloys, at least partially, with iron. On the other hand low carbon steel baths easily take up carbon whether the latter is added in a solid, liquid, or gaseous condition, either in the elementary form or as carbon containing alloys such as ferro-manganese, etc.

**Oxygen.**—Oxygen may occur in steel combined with other elements, for example, as CaO, $SiO_2$, MnO, $Al_2O_3$, etc. These oxides are only mechanically mixed, not alloyed with the steel, and they are usually classed as "inclusions." Such inclusions are undesirable in high quality steels for they loosen the structure, and so lower the physical properties. In addition to this, however, steel can contain oxygen in the form of ferrous oxide, and such a constituent is especially to be feared for it alloys with the metal, and. like sulphur, brings about red shortness.

It is possible to remove this ferrous oxide from the metal by chemical means, reducing it by other elements according to the equation:

$$FeO + X = XO + Fe.$$

Elements that can serve as reducing agents for ferrous oxide must answer the following requirements:

(1) They should not bring about any development of gases in the reduction, for then the metal does not cast quietly, and opportunity is given for the formation of gas inclusions. Therefore reduction by means of carbon or carbides, electrodes, etc., is bad, because the formation of carbon-monoxide is the result.

(2) They must have a high volatilization temperature. Therefore the alkali metals are bad to use, for they escape from the bath for the most part as gas without bringing about reduc-

tion. This is altogether apart from their strong attack on the brickwork.

(3) They must easily reduce the ferrous oxide, and for this it is necessary that the metal should dissolve in the bath. In this way only is a complete contact and reaction possible.

(4) They must easily slag off, and separate from the metal.

Manganese, silicon, aluminum, etc., are generally used as reducing agents, and, recently, for producing high quality steels, certain alloys of silicon with calcium, magnesium, manganese, and aluminum. At the same time vanadium and titanium should be mentioned, for their influence ought to be, in the first place, very strongly reducing on the last traces of ferrous oxide.

For ordinary purposes *ferro-manganese* is mostly used for deoxidation. Its reaction with ferrous oxide, however, only takes place very slowly, and if the deoxidation is to be moderately satisfactory a considerable excess of manganese must be added to the bath. For this reason only high manganese material can be produced which is not applicable as high quality steel for different purposes. The slow influence of the ferro-manganese is caused by the alloy having to become dissolved before it can alloy with the metal. *Solid manganese must first melt in the bath before it can carry out its deoxidizing action. Because of this the deoxidation process would be accelerated if liquid ferro-manganese were added, and by using this method the amount necessary can be considerably reduced, as the loss of manganese in the shorter time is smaller.* In the electric furnace, where the ferro-manganese works in a neutral atmosphere, the minimum amount can naturally be used for deoxidation, because the alloy has opportunity to react on the bath for a long time without danger of being burnt by hot gases. Also the necessary excess of manganese in the bath can be lowered, as the manganese can work on the bath without trouble. A disadvantage of this method of deoxidizing by means of ferro-manganese is that, with the necessarily large amount of alloy used, the carbon which is unavoidably present in the blast furnace alloy also takes a part in the reaction. It follows that the bath should be allowed to stand for a long time after the ferro-manganese addition in order to allow

the gas to escape. This gas removal is, however, only complete if the bath has been given some opportunity to take up silicon. Unfortunately, there is no clear explanation for the influence of the silicon. It either reduces the carbon-monoxide dissolved in the bath, or else it makes the metal able to unite with the gases, especially the carbon-monoxide. The latter view is the more probable, for it has been mentioned that iron has a very low melting point when exposed to heat in an atmosphere of carbon-monoxide, which is easily explained by the theory of the existence of an iron-carbon-monoxide alloy.

Silicon is moreover a very strongly deoxidizing material, and scarcely more has to be used than the amount theoretically necessary. The silica easily goes into the slag, and there is no production of gas, as the small amount of ferro-silicon used adds practically no carbon. Heats deoxidized by means of silicon can be cast quietly and easily for the reasons just mentioned.

Aluminum is also an effective reducing agent, but there is the disadvantage that alumina is produced which, on account of its high melting point, does not slag off completely and some remains as a fine net-work in the metal, lowering the physical properties of the latter. In the production of high quality material the use of aluminum is therefore not to be recommended, above everything no aluminum should be used while pouring into the moulds, for then much less heat is present for melting the alumina than in the furnace.

Recently alloys of vanadium and titanium have been recommended, the latter produced by the Goldschmidt reaction. They are very effective, but at present their high price limits their use. It may be, however, that the price of vanadium will be lowered when the alloy can be produced in the electric furnace, but due to the formation of carbides special attention must be paid to the making of a low carbon vanadium alloy.

Deoxidation requires that during the whole process there should be a purely neutral or reducing atmosphere. Formerly this condition was only obtained in the graphite crucible, silicon being reduced from the crucible walls by carbon, and forming the reducing agent. For this reason crucible steels made from

a pure charge were, up to the present time, the best obtainable, although low silicon material was only produced with very great difficulty because of the silicon reduced from the acid crucible walls. The melting of low silicon crucible steels had to be done, therefore, in costly alumina crucibles.

## FLUXES, FERRO ALLOYS, ETC., USED IN THE ELECTRIC FURNACE

(1) *Ferro-manganese.*—For reasons of economy the ordinary blast furnace product is used with the average analysis—

| | |
|---|---|
| Manganese | 80.00% |
| Silicon | 1.20% |
| Phosphorus | 0.25% |
| Carbon | 6.00% |

The rather high phosphorus content can be neglected, for only a small percentage of ferro-manganese is used so that the phosphorus of the charge is practically not increased. Occasionally, pure manganese, which is naturally very expensive, is used for special purposes.

(2) *Ferro-chromium.*—Here also the cheap high carbon material is usually good enough, with the analysis—

| | |
|---|---|
| Chromium | 64% |
| Carbon | 8–9% |

especially when the alloy is added liquid. The carbon does not produce any gas, for the alloy is only added after the bath is deoxidized. Of course the carbon of the alloy must be considered in figuring the carbon of the steel. The more expensive low carbon alloys are, however, used in many cases.

(3) *Ferro-silicon.*—The best is the ordinary 50 per cent. electric furnace grade. High silicon blast furnace pig irons can indeed be used, especially with such a market as the present, but the carbon of this grade of material is higher than desirable. In making high silicon steels, such as dynamo plates, etc., the 90 per cent. alloy is used.

(4) *Lime.*—This should, of course, be as free from sulphur and phosphorus as possible. In burning the lime it should be par-

ticularly remembered that with the use of high sulphur fuel, such as is generally employed, the lime takes up considerable sulphur, so that with large pieces of lime the sulphur is highest at the outside and decreases towards the centre.

| *Analyses* | I | II |
|---|---|---|
| Outer shell..... | 0.50% S | 0.48% S |
| Middle part..... | 0.21% S | 0.20% S |
| Core..... | 0.05% S | 0.06% S |

One is therefore bound to consider the use of raw limestone, especially for the formation of the refining slag. As lime free from sulphur is needed, the stone could be burned in a shaft or rotating furnace by means of waste gases, so far as they are available. Moreover, tests with the ring furnace have shown that the lime in a chamber does not show the same increase in sulphur at all parts of the chamber. An example is given below.

The raw limestone used was very uniform and had 0.05% S. Tests taken from the material after being burnt showed the following results:

| | |
|---|---|
| Average test from the wall of the chamber..... | 0.11% S |
| " " in front of the fire..... | 0.16% S |
| " " somewhat further from the fire..... | 0.16% S |
| " " at the door..... | 0.09% S |

As lime burnt in the ring furnace is mostly used for other purposes, one is in the position to take the low sulphur part and use it specially. If burnt lime is bought it is well to consider the percentage of moisture and carbon-dioxide contained. On the other hand a small proportion of carbon-dioxide is not a great disadvantage to the process, for the slag must finally show a certain amount of carbon-dioxide, at least for desulphurizing and deoxidizing. Also certain percentages of magnesia in the lime are a disadvantage as it makes the slag less fusible.

(5) *Fluor-Spar.*—This should be as low as possible in sulphur and phosphorus, and is suitably paid for according to its contents of fluorine. Also contained magnesia is a disadvantage.

(6) *Iron Ore for the Carbon Refining Process.*—Any ore, even brown iron ore, can be used but high percentage ore is recom-

mended, so that the slag volume and the heat lost in the slag are not too great. Naturally, it is also better to use ore not too high in sulphur, especially if metal has to be worked that is high in carbon, sulphur, and phosphorus. Phosphorus in the ore, on the other hand, is not harmful so that minette ore can be used, for the bath cannot reduce phosphoric acid from the ore.

(7) *Carbon.*—A material should be chosen that is low in ash, sulphur, and volatile matter. Graphite, anthracite, petroleum, coke, etc., can be used according to one's wish and the market price. Below are given several analyses of these materials:

| | Vol. matter | Ash | Sul. |
|---|---|---|---|
| Petroleum coke..... | 3.5% | 0.7% | 1.2% |
| Retort carbon..... | 0.6 | 1.8 | 1.2 |
| Flake graphite..... | 1.3 | 6.9 | 0.5 |

They are best used in moderate sized pieces. If finely divided material must be used it is best to weigh it out into bags, or else briquette it.

## THE ELECTRIC FURNACE AS A MELTING FURNACE FOR IRON AND STEEL, AND IRON ALLOYS OF EVERY KIND

The advantages of melting in the electric furnace are chiefly brought about by the possibility of maintaining purely neutral or reducing atmospheres, which means that the hot materials do not attack the furnace walls as in the cupola, air furnace, etc.

As is well known the melting of pig iron, etc., in the cupola is attended with a considerable absorption of sulphur, which sensibly affects the final quality. For instance:

| | C% | Si% | Mn% | S% |
|---|---|---|---|---|
| Material before melting .... | 3.50 | 2.90 | 1.20 | 0.035 |
| After melting once..... | 3.40 | 2.70 | 1.10 | 0.055 |
| After melting twice..... | 3.30 | 2.50 | 0.80 | 0.073 |

Foundries making low sulphur material such as high quality castings, malleable iron castings, etc., must therefore melt either in the open hearth or air furnace, and notwithstanding this most expensive operation the undesirable action of the furnace gases

on the charge is not prevented, as is shown by the following analyses:

*A. Melting of Pig Iron:*

| | C% | Si% | Mn% | S% | P% |
|---|---|---|---|---|---|
| (1) Before melting | 3.30 | 1.55 | 1.67 | 0.053 | 0.36 |
| Finished material | 3.25 | 0.66 | 0.76 | 0.083 | 0.37 |
| (2) Before melting | 3.18 | 0.59 | 1.79 | 0.075 | 0.27 |
| Finished material | 3.16 | 0.22 | 1.22 | 0.093 | 0.27 |
| (3) Before melting | 3.06 | 0.72 | 1.98 | 0.069 | 0.23 |
| Finished material | 3.02 | 0.28 | 0.28 | 0.090 | 0.23 |

The melting in all these cases took place in an air furnace, using bituminous coal with about 0.7% sulphur.

*B. Steel Castings Melted in a 5-Ton Open Hearth Furnace.*

| | C | S |
|---|---|---|
| (1) Before melting | .... | 0.050 |
| Finished material | 0.30 | 0.060 |
| (2) Before melting | .... | 0.037 |
| Finished material | 0.25 | 0.050 |
| (3) Before melting | .... | 0.048 |
| Finished material | 0.45 | 0.062 |

Naturally those plants suffer which have to use, anyhow, high sulphur pig iron and fuel; on the other hand, with melting in the electric furnace there is no oxidation of the iron nor of the valuable constituents silicon, manganese, etc., such as is shown in the above analyses. As is well known in the melting of an ordinary foundry iron, a loss of at least 10% of the silicon is calculated, with higher silicon irons still more, and on this account less scrap can be melted than the silicon of the cold foundry iron would allow. In electric furnace melting there is no loss of iron, nor metal loss in the slag, for no melting slag is necessary.

Electric melting is particularly important in the production of hard castings. The *high manganese pig iron* used suffers a high loss of manganese in melting in the ordinary furnace, *which is entirely absent with electric melting*, so that the amount of the expensive high manganese iron necessary can be considerably lowered. An important point that recommends the electric

melting of iron for foundry purposes is that in the electric furnace the temperature can be governed as desired. The percentage of bad castings therefore ought to be somewhat reduced, for the casting of cold iron, which may happen with the cupola even with the most careful supervision of the operation, is excluded. Also in regard to the quality of the castings, electric melting should bring about considerable improvement, apart from the avoidance of an increase in sulphur, especially for pipe and thin walled castings, for which high phosphorus brittle material has now to be used in order to fill out the moulds. As it is possible to increase the temperature of a low phosphorus iron in the electric furnace to such an extent that the same fluidity is produced as with a high phosphorus iron, one can therefore, under these conditions, produce thin walled castings from low phosphorus iron which is not brittle, without getting porous or blowholy castings.

The electric furnace is also very suitable for melting ferro-manganese, and all the ferro alloys, which are so much used in steel plants and also recently in foundries. Every metallurgist knows that for quickly completing heats of steel in the furnace or in the ladle, considerably more ferro-manganese must be used if it is added cold than if added liquid. In spite of this, up to now, he has been forced to be satisfied with the use of solid preheated ferro-manganese, because the metallurgical furnaces available for melting this easily oxidizable material are not practical as the loss increases immeasurably. *The electric furnace is here particularly applicable, for with a reducing atmosphere an oxidation of the manganese is excluded.* Arc furnaces will not be so suitable for this purpose, for on account of the overheating of the bath near the electrodes the manganese will vaporize, and at the same time the furnace lining will be strongly attacked by the manganese vapor. The introduction of the electric furnace into foundries, steel works, etc., will be further favored by the fact that during the melting an excellent mixing of the charge will take place. Until now in cupola melting one is compelled to take the metal more or less as it comes, even when making a special material, because though one may know the

composition of the material charged it is difficult to figure on the loss during melting, and therefore on the final composition. With the electric furnace on the other hand, where there is no oxidation, one can calculate exactly beforehand the composition of the final fluid metal, apart from the fact that an absolutely uniform material, free from impurities, will be produced. Bad heats, because of low or high silicon, will be excluded because one can add to the bath the right amount of ferro-silicon on the one hand, or low silicon pig on the other. Attempts have often been made previously to increase the silicon in a low silicon iron by the addition of ferro-silicon to the casting ladle, a process that is only partially successful, for, to absorb the silicon, it must be first melted, which requires a very hot bath of metal and also a certain amount of time. Both conditions are fully met in the electric furnace, but not in the casting ladle.

Also cast-iron scrap, turnings, etc., can be melted without the scrap being for the most part burned and slagged off as in the cupola. Indeed, this great loss, when melting fine material such as turnings, etc., in the cupola, has forced those plants which have considerable amounts of such scrap to briquette it before melting. The considerable cost of this process is always lower than the saving due to the decreased loss. Also, a low carbon material, similar to cold-blast iron, can be produced without difficulty by the melting in of wrought-iron scrap.

The melting of pig iron in the electric furnace can, at the same time, be combined with a refining of sulphur or silicon. In regard to the sulphur its removal is easy if a lime slag is produced. As the silicon content of the pig iron is almost always high enough, desulphurization readily takes place according to the equations given before, if there is temperature enough. The sulphur enters the slag, which is drawn off. Such desulphurized iron is particularly suitable for malleable iron castings, so that even for this high grade material a cheap high sulphur iron or scrap can be used. The lowering of the silicon will naturally be brought about by the addition of a correspondingly low silicon iron.

As a conclusion it may be taken that the electric furnace will

find a place in foundries, etc., for melting pig iron, ferro alloys, etc.; particularly in the production of high quality material. The advantages are an absence of loss by melting and in the slag, the production of the same metal as calculated theoretically, the use of cheap high sulphur iron, and the melting of more cast-iron scrap. In general the induction furnace will be preferable for these purposes, for the bath is heated uniformly and there is no electrode action on the metal which would give loss of manganese because of vaporization.

The profitable use of the induction furnace in the melting of fine scrap must be particularly mentioned, for there is always a bath of metal in the furnace. On charging the cold scrap it immediately falls into this bath and is therefore protected from oxidation. The power consumption per metric ton of steel scrap melted in this type of furnace is about 580 kw. hrs., an amount that makes electric melting appear quite economical, when it is considered that the great loss present with any other kind of melting is entirely absent.

### THE ELECTRIC FURNACE AS A MIXER

Most large steel works that have several blast furnaces, as well as foundries taking metal direct from the blast furnaces, already have mixer plants either to regulate the production, to get a better mixture of the different casts, or to obtain as thorough prerefining as possible. This means a separation of the sulphur brought about by a part of the sulphur slagging off as a sulphide of manganese, if there is sufficient manganese in the iron. The size of the mixers varies a great deal from 25 to 1,000 tons and more capacity. The small mixers are preferably used for iron foundries such as pipe foundries, that take direct metal, but the prevention of cooling with the small mixers is naturally not very good so that sometimes heating is necessary. If refining is desired in the mixer, then heating by means of fuel is not so profitable and there is opportunity for the electrically heated mixer, which will be similar to an ordinary electric furnace of very large size. Furnaces of more than 25 metric tons capacity have, however, not yet been built, so that in this respect there

has been no experience. The requirement for an electric mixer is that the metal should be held at the right temperature. The question should be best solved by an induction furnace, for here the temperature can be kept at any desired degree, and there is also certainty of an absolute uniformity of the whole metal because of the movement of the bath. In the mixer there would also be a thorough desulphurization of the metal, so that the product would undoubtedly meet the most rigid requirements of quality.

On the other hand, if the mixer metal is to be used for steel making, and then subjected to subsequent refining processes, heating with ordinary fuels would still in most cases be the more economical.

Further, here again the known calculations give weight on one side or the other, namely, which is the more expensive under the conditions present, heating with electricity or direct heating with fuel.

### THE REFINING OF PIG IRON

The refining of pig iron can be carried out very well in the electric furnace, and just as well by the oxygen of ores as by that of the air. In general the induction furnace here also would come mainly into consideration, for, as mentioned above, the refining process can only be carried out in the arc furnace with great electrode loss, and use of considerable refining material.

The iron could be melted direct in the electric furnace, or the liquid metal could be charged from the blast furnace, mixer, cupola, open hearth or special furnaces, after the liquid metal had been previously refined, that is desulphurized, etc.

Refining with ore in the electric furnace is, however, expensive because the reduction of the ore takes place slowly, exactly as in the Talbot, Bertrand-Thiel, and other processes, so that the current consumption caused by radiation is too great. In order to accelerate this reduction, and so save electric energy, one could consider charging the ore highly heated, if peat or some other fuel not suitable for steel works furnace operation is readily accessible. Concerning the thermal advantages brought about

by the use of highly heated ore, the following approximate rough calculations give some information.

The pig iron contains 3% carbon, and will be refined by pure magnetite heated to 800° C. According to the equation:

232 kg. $Fe_3O_4$ + 48 kg. C = 168 kg. Fe + 112 kg. CO,

the 30 kg. carbon that are in a metric ton of iron require $\frac{232 \times 30}{48}$ = 145 kg. ore. This amount of ore heated to 800° C. holds $145 \times 0.2 \times 800 = 23200$ cals., which equals $\frac{23200}{864.5} = 26.8$ kw. hrs., an amount that helps the electric furnace considerably, so that the use of preheated ore is worth consideration, if the cost of preheating is not too high.

There are also proposals to carry out air-blast refining, similar to the Bessemer, in the electric furnace. With arc furnaces the electrodes would have to be drawn up high during the blowing, so that during this operation no heat would be supplied, and the bath would chill, if there were not sufficient silicon and phosphorus present to balance the heat lost, and bring the metal to the casting temperature of soft steel. In this case the bath must be alternately electrically heated, then blown for a short time, but this gives so many operating troubles that the intended saving due to time saved with blowing is not realized.

Iron low in silicon and phosphorus, that cannot be handled by either the acid or basic Bessemer, may be refined with a blast of air in the induction furnace, for here the bath can be heated during the blow. The following rough calculations give some information on the probable results with a 10-ton furnace and a pig iron with 3% carbon, and a temperature of 1300° C.

10 tons iron contain 300 kg. carbon, which would require (12 C + 160 = 28 CO) $\frac{16 \times 300}{12}$ = 400 kg. O, 100 kg. air contain 23 kg. O, so that 400 kg. O correspond to $\frac{400 \times 100}{23}$ = 1740 kg. air. The temperature of the bath must be raised from 1300° to 1650° C., that is 350°C.

The blast may leave the bath at an average temperature of

1500° C., although this value is probably too small, for the carbon in the bath heated to 1300° C. will burn at a high temperature, and it appears doubtful whether the very hot gas produced will give its heat to the bath completely enough to escape at only 1500° C.

There is therefore the following amount of electric energy conducted to the bath.

| | | |
|---|---|---|
| 10000 kg. iron heated 350° C. | $10000 \times 0.2 \times 350$ | = 700,000 |
| 1740 kg. air heat to 1500° C. | $1740 \times 0.3 \times 1500$ | = 783,000 |
| | | 1,483,000 |

Brought in:

| | |
|---|---|
| 300 kg. C burnt to CO ..... | 741,900 |
| Leaving ..... | 741,000 |

This corresponds to $\frac{741{,}000}{864.5}$ = 857 kw. hrs.

Therefore an electric induction furnace of 10 tons capacity will operate with about 800 to 900 kw. hrs. If the efficiency of the furnace is taken as 60%, then 480 to 540 kw. will be sufficient to heat the bath. This shows that the carbon can be thoroughly removed, in $\frac{857}{480}$ to $\frac{857}{540}$, that is 1½–1¾ hours. The time interval under these conditions compared with that of the other air-blast refining processes is very considerable. Air-blast refining must therefore be carried out extremely slowly, or, with frequent interruptions. The proposals to refine in this way have so far found no practical application.

From all this it follows that, if there is a mixer available it is a good thing in all cases to bring about as complete refining as possible in the mixer, and so relieve the electric furnace. Better economic results are obtained in refining pig iron if large amounts of mild steel scrap are available to melt with it, so that only a hard steel-like product remains to be treated.

The problem of pig-iron refining in the electric furnace now approaches solution, because, for example, for railroad material there is an inclination to use harder qualities of steel than are

used now. If, in a case like this, the pig iron to be used is sufficiently low in phosphorus so that no refining is necessary, to give a steel low enough to meet specifications, then carbon alone has to be removed. In such a case the electric furnace could work economically in many places. Also with specifications calling for very low phosphorus in the steel the bath high in carbon and phosphorus can be dephosphorized without removing the carbon, as mentioned above, by keeping the temperature low and forming an easily fusible basic slag, containing oxide of iron, which is drawn off when the phosphorus is low enough in the steel.

The refining of pig iron in the electric furnace is not advantageous if a low carbon, absolutely phosphorus free, material has to be made from a high phosphorus pig iron. In order to remove the phosphorus the carbon must first be completely taken away, and the bath even overrefined to a certain extent. In general for this purpose the electric furnace cannot compete economically with the open hearth. Further, in this case the cost of fuel and of current have to be weighed against each other.

If the pig iron to be refined is high in silicon, as well as phosphorus, two electric furnaces can be used, one with an acid lining for removing silicon and carbon, the other with a basic lining to remove the phosphorus. Still such an iron can be worked in the basic furnace in which case a sufficient amount of lime must be added to prevent the lining from being attacked. Finally, the deoxidation, etc., can be carried out in a third furnace with an acid lining, or in crucibles, and many combinations of the crucible, open hearth furnace, mixer, converter, etc., are possible, the suitability of which must be decided for each separate case.

The output when refining with ore is extraordinarily high, because there is no loss and because of reduction from the ore, so that it is over 100%.

## THE PRODUCTION OF SPECIAL QUALITY STEEL IN THE ELECTRIC FURNACE

High quality steel production aims at the melting of the softest to the hardest qualities as desired in both alloy and plain steels. Steels that will meet the most rigid requirements in regard to low sulphur and phosphorus on the one hand, and on the other hand be as free from oxygen as possible and in this respect be equal to crucible steel.

The best material up to the present has been made by the crucible process, special care being paid to the kind of raw material charged. The use of the purest materials is a first requirement for the crucible process, for naturally no removal of sulphur and phosphorus is possible to any considerable extent. Indeed this dependence on certain kinds of iron, which meet the guarantee of absolute purity, altogether apart from the cost, has finally been the reason for the introduction of the electric furnace, as it made the material forming the charge independent of a fixed source of supply. The general strike in Sweden during 1911 has opened the eyes of the leaders in this industry to the disadvantages that may come when one is forced to use a certain material alone.

In comparison with this the electric furnace offers the great advantage that it is not dependent on any certain special raw material, for the most impure materials can be refined so that they become even better than the purest Swedish charcoal iron in regard to purity from phosphorus and sulphur. At the same time deoxidation takes place just as completely as in the crucible because a purely reducing atmosphere is maintained, the steel can be held as long as desired, and the temperature can be regulated with more certainty than in furnaces heated with fuel. Similar conditions are not offered by any other metallurgical furnace, for in them the action of the flame on the bath cannot be entirely prevented.

From all this it is seen that electric steel is at least of equal value to crucible steel, for it can be produced practically free from phosphorus, sulphur, and non-metallic inclusions. There-

fore the use of the electric furnace gives the advantage, that in it ordinary low carbon steel can be improved and made equal to the very best qualities of crucible steel, for from the low carbon steel:

(1) Phosphorus and sulphur are completely removed.
(2) It is totally deoxidized.
(3) It is freed from slags and inclusions.
(4) It is accomplished at a lesser cost per ton.

### PRODUCTION OF SPECIAL QUALITY STEEL IN THE ELECTRIC FURNACE FROM PREVIOUSLY REFINED METAL WITH LOW PHOSPHORUS AND SULPHUR

It is a side issue in what way the steel is prerefined, whether in the converter, in the basic or acid open hearth, or in any other way. Also the material can either be charged liquid or cold, but in the latter case, the electric furnace will also be used for melting. If the electric furnace is worked in combination with an ordinary steel plant from which it obtains its charge, then it is most suitable to pour a part of the steel works charge into the electric furnace before the deoxidizing additions are made. On the other hand, if larger heats are made in the steel works than the electric furnace is able to take, or for other reasons, then the bath of steel to which the additions have already been made can be partially poured into the electric furnace. Naturally it is preferable that the electric furnace be able to take the whole heat with the restriction that the building of very large electric furnaces is at present troublesome. In regard to this the first part of the book should be consulted.

In the case we are considering, the aim of the electric furnace is to improve the steel and to produce a material of equal value to open hearth, or crucible steel, in particular:—

(1) To recarburize the bath to the required hardness.
(2) To deoxidize the bath.
(3) To bring about the removal of gas and slag inclusions.
(4) To alloy the bath as desired.

Such a process can be profitable, for example, if there is a Bessemer plant operating, and it is desired to produce from the

Bessemer steel material equal to high grade open hearth, which will be required for various purposes such as boiler plate, etc. Such material finished by the electric furnace is extremely suitable for particular purposes, so much the more that it rolls and forges well and shows considerably increased physical properties.

If material is charged into the electric furnace to which no deoxidizing additions have been made, then it has to be first completely deoxidized, and the production of steel of a satisfactory quality requires, in the first place, that this deoxidation be carried out very carefully. As shown in a previous chapter it can be done in many ways, with ferro-manganese, ferro-silicon, etc. Which of these materials should be used depends on the quality of steel that has to be produced, particularly whether it is to be a low or high manganese.

If a product is to be made as low in manganese as possible then it is best to carry out the deoxidation with ferro-silicon. Immediately after pouring the charge into the electric furnace the first addition of ferro-silicon should be made, preferably in pieces about the size of one's fist, and at the same time the bath should be covered with an easily fusible slag to exclude the air.

The kind of slag is governed by the furnace lining: with a basic hearth a neutral or basic slag is charged; with a neutral or acid hearth, on the other hand, one of greater acidity. A suitable mixture of lime and sand with more or less fluor-spar may be used to form the slag, all of proper size. In regard to the amount of slag it should be mentioned that the bath has only to be completely covered. Furnaces of greater capacity that work with a deep bath use, therefore, a lower percentage of slag than those of less capacity which expose more surface per ton.

The first addition of ferro-silicon is given, before the bath is covered with slag in order to save time in the first place, and secondly to prevent the light ferro-silicon from being enclosed in the slag, which is quite thick at first. The slag first turns black due to the absorption of oxide of iron from the bath, for a condition of equilibrium is formed between the oxide dis-

solved in the bath and the slag. For complete deoxidation it is therefore absolutely necessary that the slag contain no oxide, and so it must always be snow white. This is produced by sprinkling a suitable rêducing agent on the slag when it shows a dark color, and maintaining a neutral or reducing atmosphere. In the induction furnace fine ferro-silicon, about pea size, is used in this way, being added from time to time in small amounts. In the arc furnace this ferro-silicon can be produced from the slag if carbon is added. Which of the two methods is the cheaper we will not investigate.

If the slag keeps snow white then the melter takes pouring tests and convinces himself of the condition of the steel, and if it does not yet pour quietly, adds more pieces of ferro-silicon to the bath until a further test gives a good result. A completely deoxidized steel, melted with a white slag, must pour without trouble. Alloys such as nickel, manganese, chromium, etc., can now be added in the theoretical amounts, for no slagging of these additions can take place under the white slag covering. No preheating is necessary, and also the cheaper ferro alloys, high in carbon, can be used in the induction furnace for, due to the movement of the metal bath in this furnace, it is impossible for carbides to remain undissolved.

In making a steel with low to average manganese content it is the best to give first an addition of ferro-silicon, after which the bath is covered with slag. The final deoxidation can now be made with ferro-manganese, spiegel, etc. After this the slag will first darken, due to the manganese reacting with the oxide of iron forming MnO, which enters the slag. As mentioned above the first requirement for complete deoxidation is that the slag be snow white. The black slag produced must, therefore, be reduced in a suitable manner and made white.

In the induction furnace ferro-silicon again serves as a suitable reducing agent and carbon in the arc furnace, both of which are sprinkled on the slag. The reduced manganese goes again into the slag. It therefore passes through a cycle and really only serves as a bearer of the oxygen contained in the metal, so that the deoxidation can be carried out with very small

amounts of manganese, and a final material with a moderate percentage of manganese can be produced.

Instead of ferro-manganese, manganese ore can be used, and in the induction furnace this ore is selectively reduced by ferro-silicon rather than with carbon, but in the arc furnace on the other hand the one would be reduced by carbon under the influence of the arc. It is not necessary to consider here whether it is the cheaper to use ferro-manganese melted in the blast furnace or to reduce manganese in the electric furnace from manganese ore. The remainder of the process of melting is the same as that described under the production of steel free from manganese.

If the material has to be harder, that is higher in carbon than the material charged, then after the first addition of ferro-silicon before the slag is made, the necessary amount of carbon is added to the bath. A small excess is given, depending on the size and the physical condition of the carbonizing material used, for a part is burned as it is charged into the furnace. Then comes the slag formation, and it is well to take a test and make a quick color carbon determination to see whether the metal is of the right hardness. The further process is the same as that used for the production of low manganese steel. The temperature is held at such a degree that the small impurities caused by the reduction can separate readily and is gradually increased to the proper casting temperature. It must be remembered that the slag formation requires a certain amount of heat as also the solution of carbon, if any is added, and so cools the bath.

At the beginning of the deoxidation it is well to give an addition of ferro-silicon even when melting high carbon material. If carbon is added to the bath before the ferro-silicon then there is a vigorous action, and a considerable loss of carbon cannot be avoided. At the most, therefore, one can only add a part of the carbon before the ferro-silicon, and after the deoxidation the rest must be added in a special operation to give the hardness required. Also by the addition of carbon before the ferro-silicon scarcely any ferro-silicon will be saved, and on the other

hand it only increases the time of the operation and the work in the furnace.

If the ordinary forging and pouring tests are favorable then the casting of the heat is proceeded with. The slag also is poured into the casting ladle in order to protect the metal from the influence of the air in the first place, and secondly to prevent the slag sticking to the hearth of the empty furnace, and attacking the lining. Due to the total deoxidation the electric steel casts so quietly that the addition of aluminum to the stream during pouring is absolutely unnecessary, so that in this respect the quality of the metal does not suffer. Casting is carried out in just the same way as in plants making high quality steels.

As a conclusion it may be mentioned that during this finishing process considerable desulphurization is brought about by the silicon present, even when it is not intended, so that in this respect the after treatment of low carbon steel in the electric furnace means a rather considerable improvement in quality.

If an addition of ferro-manganese for deoxidation has already been made in the converter, open hearth, etc., then after pouring into the electric furnace an easily fusible basic slag alone has to be made and kept constantly white, that is free from oxide. This is brought about as mentioned above by ferro-silicon in the induction furnace or just as well by carbon in the arc furnace, where silicon is reduced from the slag by the influence of the arc. This assumes that the steel poured into the electric furnace already contains the necessary percentage of silicon, but if this is not the case then before the formation of the slag the corresponding addition of ferro-silicon is given. Naturally in this process also there is a lowering of the sulphur of the charge, even if such is not intended.

### PRODUCTION OF SPECIAL QUALITY STEEL IN THE ELECTRIC FURNACE FROM PREVIOUSLY REFINED METAL WITH CONSIDERABLE PHOSPHORUS AND SULPHUR

Here also it does not matter in what way the steel is prerefined, or whether it is charged hot or cold so that the electric furnace has to be also used as a melting furnace. The aim of

the after treatment in the electric furnace is to raise the quality either to that of open hearth or the best crucible steel. The metallurgical process in the electric furnace must therefore improve the steel in regard to the following points:

(1) Eliminate the phosphorus.
(2) Deoxidize and desulphurize.
(3) Remove the gas and slag inclusions.
(4) Recarburize or alloy according to requirements.

In regard to the removal of phosphorus and sulphur both elements cannot be removed from the bath in one operation, for the removal of the phosphorus takes place by an oxidizing or refining process, and that of the sulphur, on the other hand, by a reducing process:

$$FeS + CaO + C = Fe + CaS + CaO.$$

These operations must, therefore, be carried out one after the other, and it is similar in principle whether the bath is desulphurized first and then dephosphorized, or, on the other hand, dephosphorized first and then desulphurized. Which of the two ways is the most suitable depends on the composition of the charge that is put into the electric furnace and on the kind of steel to be produced.

If the metal as charged has had no additions so that it is not yet deoxidized, then it is best to dephosphorize first of all as the necessary conditions are present. The total removal of the phosphorus requires an overoxidation of the bath, so that the metal gives a seamy, that is a red short, forging test. When using a charge that is still oxidized therefore only a basic slag has to be charged to favor the soaking of the bath with oxygen, and at the same time give conditions so that the phosphoric acid formed is immediately combined with lime. The requirements in regard to freedom from sulphur on the part of the slag-making materials are not particularly high, for the bath has to be desulphurized afterwards anyhow, but it is well to use materials as low in sulphur as possible, so as not to raise the sulphur in the bath. Also the phosphorus percentage of the ore is without influence, for an oxidized bath cannot reduce phosphorus, and

is therefore unable to take phosphorus from the ore or limestone.

If it is desired, on the other hand, to desulphurize first then the bath must be first completely deoxidized, and after the removal of sulphur the bath must be oxidized again to remove the phosphorus. The whole manipulation of the deoxidizing, therefore, gives no lasting result, and at the same time only the purest ore and limestone can be used to form the refining slag so as to prevent absorption of sulphur by the bath.

On the other hand if the charge has already had an addition of ferro-manganese in the converter, open hearth, etc.; and if a very soft steel has to be made with the lowest possible phosphorus and sulphur and also practically free from silicon, then it is best to desulphurize first. In this way one can work with a small amount of silicon, and the low silicon remaining in the bath is removed during dephosphorizing. The heat is then finished with the addition of ferro-manganese, and is cast just as in the open hearth process, keeping the slag back. Here also it is necessary to use ore and lime free from sulphur to prevent the bath again taking up sulphur during the subsequent operations. The quality produced is, however, only equal to that of good open hearth not crucible steel. If sulphur-free burnt lime is not available then it is well to use raw limestone if the sulphur is low enough. Apart from this and some other special cases the charge, prerefined and then poured into the electric furnace, will always be dephosphorized first whether deoxidizing additions have been already given in the preliminary furnace or not. This is done because: (1) With desulphurizing first the silicon used is again removed during the dephosphorizing. Therefore the amount of ferro-silicon used is unnecessarily increased; (2) the total deoxidation, which is necessary for desulphurization, would be made of no use by the subsequent oxidation, (3) the ore and limestone used for the refining slag have to be very free from sulphur.

Immediately after pouring the charge into the electric furnace a refining slag should be formed with ore and lime. The size of these materials should not be too great as otherwise

they only fuse together with difficulty, that is, the formation of the slag takes too long and the time of the heat is increased. On the other hand there is no limit to the fineness of the material, so that, for example, unbriquetted concentrates can be used. The burnt lime is best broken up just before charging, for it quickly takes up moisture and carbon-dioxide from the air.

The amount of slag necessary is proportionally small, especially if dephosphorization has already taken place to some extent, for instance, to 0.1%. The bath need not be well covered by the slag, although dephosphorization naturally takes place more quickly if the slag covering is not too small. On the other hand it is well not to unnecessarily increase the amount of slag so as to avoid loss of heat. In the induction furnace, work in a high manganese charge, that is one already deoxidized in the first furnace, it is well to make a slag with 1% ore and 2% lime of the weight of the charge. If the forging test shows that the bath has the right percentage of phosphorus, then the slag is drawn off, and the last traces removed by means of fresh lime thrown over the bath. This thickens the remainder of the slag so that it can be easily removed.

If a high phosphorus charge is to be worked, then it is well not to charge the whole amount of slag necessary at one time for, as mentioned before, it is not recommended to work with too large a slag volume in the electric furnace. In this case it is better to charge the ordinary small amount of slag, remove it when completely used up, and then form a new slag of the same weight. This should be repeated as required. Such a case can happen in practise if the electric furnace charge is taken from a heated prerefining furnace, such as a Wellman-Talbot furnace, in which by exceeding the capacity a material is produced that is high in phosphorus.

If the electric furnace is to be used continuously for the refining of such high phosphorus charges, then it is well to figure on this in the construction of the furnace. A shallow bath but a large surface should be used in order to give the refining slag a large attacking surface, and to shorten the time of the process. On the other hand the surface of the bath should not be too great

for, in this way, the radiation loss increases and the efficiency of the furnace drops. These are important points for the designers of the furnace, namely, to make the hearth the right size and shape to properly meet the conditions, and in this respect experience obtained with open hearth furnaces will be valuable. If a high phosphorus charge is worked, with several refining slags, then the first slag is very low in iron but high in lime and phosphoric acid. These slags are of some value in agriculture as low phosphate slags, so that they need not be thrown away. The succeeding slags, however, are rich in oxide of iron and low in phosphorus, and can be used as a first slag for subsequent heats and so be used more completely. If the fluxes are used to exhaustion then the consumption of ore and lime, in reference to the finished material, is considerably reduced.

The bath can now be deoxidized, carburized, and desulphurized. The removal of the oxygen and sulphur takes place together, the first by means of ferro-silicon, carbon, or ferro-manganese depending on the kind of material to be melted; the latter by the addition of ferro-silicon and in the arc furnace by silicon or calcium reduced from the slag by carbon under the influence of the arc.

First an addition of ferro-silicon is made that can be a little more in amount than is necessary for deoxidation alone because of the desulphurization also taking place. In general the operation is exactly the same as described in the previous section, namely: "The production of electric furnace material from previously refined metal with low phosphorus and sulphur."

It may be mentioned that tungsten has similar desulphurizing properties to silicon, so that tungsten heats can also be made extremely low in sulphur.

A peculiar phenomenon must be mentioned which can happen under certain conditions with non-expert handling of the electric furnace. As already said a well deoxidized charge pours quietly, and only pipes a little on solidifying, depending on the temperature and the silicon. On the other hand, if the heat is made too hot, if the bath is not completely covered with slag, if air can enter the furnace, or if the deoxidation slag is

not kept sufficiently free from metal, then the steel casts very badly, even though it may contain several tenths per cent. of silicon, the forging tests will show the properties of an oxidized material. The causes for this phenomenon are not at present very clear, but it appears probable that at high temperatures a part of the silicon occurs dissolved in the metal as a suboxide, probably with the formula SiO. Because of the similarity between silicon and carbon the possibility of an alloy of iron and silicon-suboxide can be thought of, for, as mentioned before, the existence of an alloy of iron with carbon-monoxide is probable.

## THE METALLURGICAL COURSE OF AN ELECTRIC FURNACE CHARGE

The course of the metallurgical reactions in the Héroult and the Röchling-Rodenhauser furnace is given in the two accompanying diagrams (page 398). The curves for the Héroult furnace were published by Thallner in No. 5, 1909, of *Kohle und Erz*, and are taken from a heat in a 3-ton furnace; while the diagram of the Röchling-Rodenhauser furnace is taken from an ordinary heat made at Völklingen in an 8-ton alternating current furnace built up to take 5 to 6 tons.

From a comparison of the two diagrams it is seen first that the time of heat in the Héroult was twenty minutes longer than in the Röchling-Rodenhauser furnace, notwithstanding that the former was only worked with a 3-ton heat, while the latter had 5 tons.

Also, the material made in the Röchling-Rodenhauser is at least just as pure as that produced in the Héroult, notwithstanding that a much more impure charge was worked in the former. The oxidation period is distinguished, in the Röchling-Rodenhauser furnace, especially at the beginning, by an extraordinarily quick removal of the phosphorus and manganese from the steel. For instance, in the first twenty minutes the phosphorus drops from 0.06 to 0.025, that is 0.035%, while in the Héroult furnace it is only lowered from 0.03 to 0.02, that is 0.01%, in the same time.

Also the manganese drops from 0.49 to 0.12, that is 0.37% in

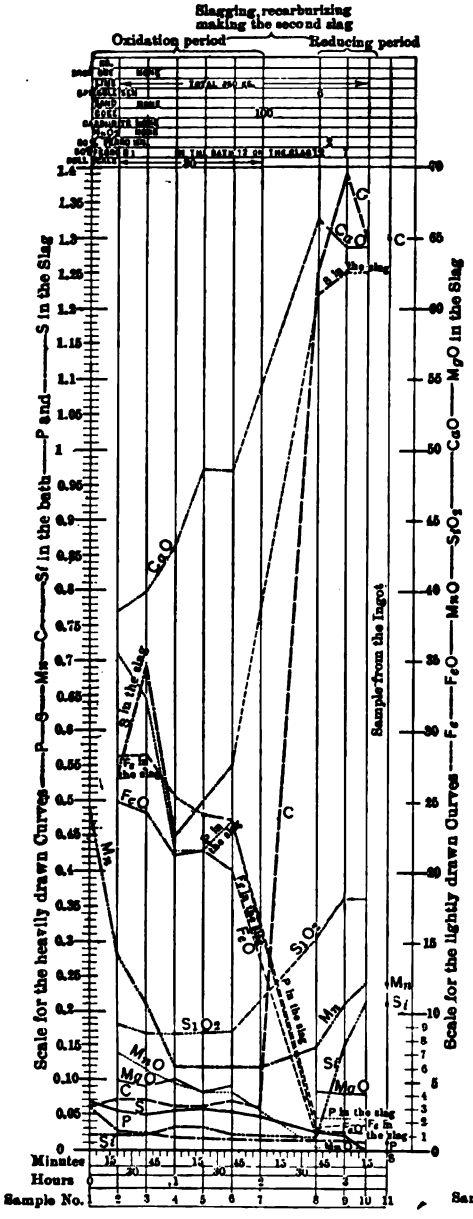
the first hour in the Röchling-Rodenhauser furnace, while in the Héroult furnace in the same time it is only lowered from 0.21 to is 0.1%.

From this it follows that the Röchling-Rodenhauser furnace must be considered as a good oxidizing furnace. The lowering of the phosphorus content of the slag, which is to be noticed during the oxidation period with both furnaces, is due to the slag being diluted from time to time by the addition of roll scale.

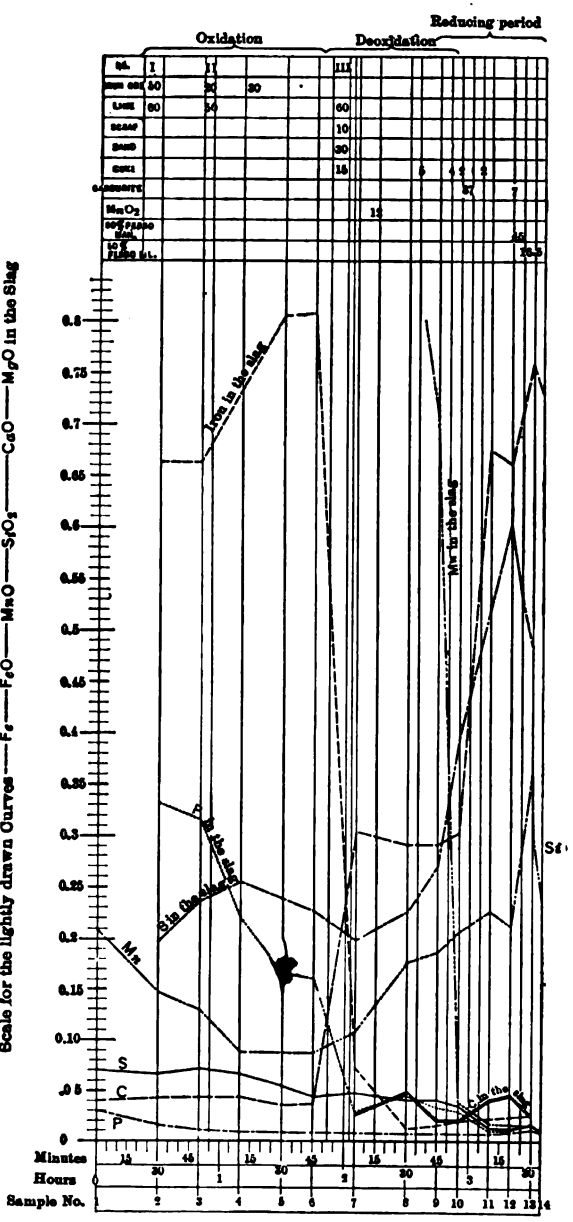
The removal of sulphur during the oxidation period is relatively unimportant with both furnaces, and only after the recarburization, or after the formation of the final slag, does the real desulphurization begin. During this period the sulphur is lowered in the Héroult furnace from 0.07 to 0.012%, while in the Röchling-Rodenhauser a desulphurization from 0.065 to traces is brought about. That the ability of the slag in the Röchling-Rodenhauser furnace to absorb sulphur is at least as great as that in the Héroult furnace is seen from the sulphur content of the slag, which is 1.25% in the first case, and only about 0.06% in the latter as shown by the curves. The amounts of slag-making constituents used in both cases are shown in the diagrams, so that all the details of the refining operation are given that are of interest.

### THE SPECIAL QUALITIES OF ELECTRIC IRON AND STEEL

As already shown any material from the mildest to the hardest quality can be made in the electric furnace. Electric furnace material is distinguished by its freedom from gas and slag inclusions, and can easily be produced with very low manganese and completely free from phosphorus and sulphur, and as soft and forgeable as the Swedish qualities. This low carbon electric steel can easily be alloyed, for instance with silicon, for making material for dynamo plates, etc., the production of which in the open hearth furnace is troublesome because of the necessary low casting temperature. The use of the electric furnace for this purpose means, therefore, considerably easier operation. Also the softest material can be flattened out very thin without showing red shortness, and can be used for punching


Slagging, recarburizing making the second slag
Oxidation period
Reducing period
Scale for the heavily drawn Curves—P—S—Mn—C—Si in the bath—P and—S in the Slag
Scale for the lightly drawn Curves—Fe—FeO—MnO—SiO2—CaO—MgO in the Slag
Sample from the Ingot
Minutes
Hours
Sample No.

Refining curves for the Röchling-Rodenhauser furnace.




Refining curves for the Héroult furnace.

and deep drawn work, deep stamping, etc., for everything where value is put on good malleability; also for the production of chains, the making of tools, etc., and further in those cases where especially soft open hearth qualities from Sweden must be used, such as seamless tubes, horseshoe nails, etc. On account of its purity this low carbon electric steel is much less inclined towards segregation than ordinary low carbon steel, and on this account should be particularly used where the highest requirements of absolute certainty against brittleness are necessary.

In the electric furnace construction steels of any degree of hardness can be produced, of any desired physical properties and chemical analysis, also alloyed with chromium and nickel where it is a question of meeting the highest specifications. These steels at present must be made in the crucible.

With the large heats[1] possible in the electric furnace a certainty of absolutely uniform composition is guaranteed for the finished steel, such as is suitable for the production of large forgings low in manganese. The electric furnace material can be easily hardened, and on account of its homogeneity and freedom from slag is an excellent material in such cases where the surface must be dense* and highly polished and show no cracks, such as running taps, etc. In general Plates 3 and 4 show what high requirements are in every way satisfied by electric steel.

## FINAL CONSIDERATIONS

For the smelting of ore the electric hearth as well as the shaft furnace is to be considered, and in each particular case it must be carefully decided which type of furnace has the advantage. If very finely divided ores, high in sulphur, are to be worked up into steel by means of small sized reducing material, then the induction hearth furnace should be chosen because of the possibility of producing steel direct from such raw materials of any quality desired. Also because when changes have often to be

[1] See Osborne Amer. Electro-Chemical Society, 1911, Vol. XIX.

* For quality of steel, see also Vom Baur, American Foundrymen's Association, May, 1911, page 247.

made in the kind of metal produced, the making of valueless transition products is avoided. On the other hand, if coarse low sulphur lump ore and fuel are available, then the induction shaft furnace should be chosen, especially if the same quality of metal is always to be made, and the reducing material is high in price.

The electro-thermal smelting of iron ores can naturally only be considered economically when the saving of coke, etc., compared with the ordinary blast furnace operation is greater than the expense of the necessary electric power, so that it is dependent on the local prices of coke, etc., on the one hand, and electric energy on the other. Electric ore smelting will, however, be favored when one considers that considerably less capital is necessary for the plant than for the building of an ordinary blast furnace plant with the same output. Also the depreciation, etc., per metric ton of iron produced, are considerably lower than with the ordinary blast furnace.

It must be further remembered that the quality of electric pig iron is higher than charcoal pig iron, and therefore it should command a higher selling price than the best charcoal iron. For steel making an iron can be readily made low in silicon, which only needs removal of carbon to make steel and forgeable metal. If this refining is carried out in the electric furnace, then it has to compete with the open hearth furnace. Recently Engelhardt at the meeting of the "Verein deutscher Ingenieure," in Berlin, made an interesting comparison between the open hearth furnace on the one hand, and different types of electric hearth furnaces on the other, namely the Héroult, the Girod, and the Induction furnaces.

For medium furnace sizes with these three types the production per h.p. day, with a cold charge, is taken as 20 kg. Certainly this treats the induction furnace somewhat unfavorably, for it has about 10% greater efficiency. The given power consumption corresponds to 880 kw. hrs. per metric ton of steel. The electrode consumption, according to the most recent publications, amounts to 28 kg. per metric ton in the Héroult furnace and 17 kg. in the Girod, while with the induction furnace, of

course, there is not any. The consumption per metric ton of steel is therefore:

With the Héroult furnace 880 kw. hrs. + 28 kg electrode.

With the Girod furnace 880 kw. hrs. + 17 kg. electrode.

With the Induction furnace 880 kw. hrs. + 0 kg. electrode.

In the following table the results of calculations are given to show how much the kw. hr. ought to cost in order that the electric furnace may compete economically with the open hearth furnace using a certain amount of coal per ton at a certain price. The electrodes are taken at 26 marks per 100 kg. ($61.90 per metric ton):

| OPEN HEARTH FURNACE | | | MAXIMUM COST PER KW. HR. IN CENTS WITH THE | | |
|---|---|---|---|---|---|
| Coal consumption by weight | Price of coal per metric ton | Cost of coal per metric ton output | Girod | Héroult | Induction |
| 25% | $3.57 | $0.89 | minus | minus | 0.1000 |
| | 4.76 | 1.19 | 0.0143 | " | 0.1333 |
| | 5.95 | 1.48 | 0.0476 | " | 0.1690 |
| | 7.14 | 1.78 | 0.0833 | 0.0048 | 0.2023 |
| 30% | 3.57 | 1.07 | 0.0024 | minus | 0.1214 |
| | 4.76 | 1.42 | 0.0428 | " | 0.1618 |
| | 5.95 | 1.78 | 0.0833 | 0.0048 | 0.2023 |
| | 7.14 | 2.14 | 0.1238 | 0.0452 | 0.2428 |
| 35% | 3.57 | 1.25 | 0.0214 | minus | 0.1404 |
| | 4.76 | 1.66 | 0.0690 | " | 0.1880 |
| | 5.95 | 2.08 | 0.1166 | 0.0381 | 0.2356 |
| | 7.14 | 2.50 | 0.1642 | 0.0857 | 0.2832 |
| 40% | 3.57 | 1.42 | 0.0428 | minus | 0.1618 |
| | 4.76 | 1.90 | 0.0952 | 0.0190 | 0.2142 |
| | 5.95 | 2.38 | 0.1500 | 0.0714 | 0.2690 |
| | 7.14 | 2.85 | 0.2047 | 0.1261 | 0.3237 |

It must, however, be remembered that even when producing an ordinary open hearth quality of steel in the electric furnace, material is produced with improved physical properties so that even with a continued regular output there should be a small increased price. If this increase in price is only 5%, and the price per metric ton of open hearth quality be taken as 140 marks

PLATE II

Single Tube test piece from Plate I.

($33.33), then there is a surplus per ton of 7 marks ($1.66), which with a power consumption of 880 kw. hrs. per ton makes almost 0.2 cents that the price of power may be increased over the value given in the table. It may be further mentioned that the electrode consumption figures taken by Engelhardt appear somewhat too high, in view of the most recent figures given in Part I of this book, which vary from 10 to 15 kg. per metric ton of solid charge.

Therefore the table (on page 281) may be referred to where the electrode consumption, however, is not considered at all; and where the heating costs alone are compared, on the one hand with the use of fuel and on the other with electricity. This table, therefore, gives results similar to those in the table on the preceding page for induction furnaces, with which it agrees exactly.

The result of all this is that the electric furnace will not only play an important rôle in the future, but that it is already a factor which each iron and steel plant must now carefully consider.

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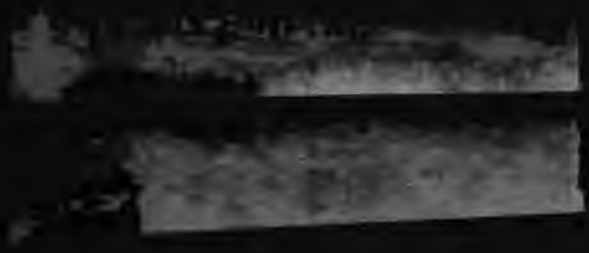

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